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SITHOK-4
Mednarodni kongres
International Congress

SITHOK - 4

OGREVANJE IN KLIMATIZACIJA
ZA TRETJE TISOČLETJE
HEATING AND AIR-CONDITIONING
FOR THE THIRD MILLENNIUM

Maribor
6. - 8.5.2000

Organizatorji:
Organisers:

Mednarodni inštitut za hlajenje
International Institute of Refrigeration

SITHOK

Univerza v Mariboru
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Uvodnik

Editorial

Ogrevanje, hlajenje in klimatizacija so temelj za kakovost življenja!

Heating, Cooling and Air-Conditioning are the Foundations of a High Quality of Life!

SITHOK 4 – 2000 je mednarodni kongres, ki ga je že četrtič organiziralo Slovensko društvo inženirjev za hlajenje, ogrevanje in klimatizacijo – SITHOK. Kongres je bil organiziran prvič v dveletnem obdobju. V času med obema kongresoma je SITHOK postal aktiven član REHVA, evropske federacije društev za ogrevanje, prezračevanje in klimatizacijo. S svojimi zastopniki sodeluje pri oblikovanju njene razvojne strategije, pri koordinaciji univerzitetnih programov na tem področju in pri oblikovanju novega znanstvenega časopisa. Mednarodni inštitut za hlajenje je bil letos prvič tudi pokrovitelj in ga je uvrstil v seznam svojih prireditev. Stalna udeležba priznanih tujih raziskovalcev in strokovnjakov iz Evrope in ZDA dokazuje, da je Slovenija, kljub svoji majhnosti, mednarodno upoštevan partner. To ni pomembno samo za člane SITHOK, ampak predvsem za slovensko industrijo, ki deluje na tem področju.

Slovenski projektanti, v pretežni meri člani SITHOK-a in seveda člani Inženirske zbornice, s svojimi projekti dokazujejo visoko usposobljenost in mednarodno konkurenčnost. Žal pa svojih dosežkov ne utegnejo prikazati domači in mednarodni strokovni javnosti, saj za to pogosto ni časa niti podpore vodilnih v podjetjih, kjer delajo. Vendar se moramo zavedati, da samo javna predstavitev dosežkov omogoča širšo mednarodno uveljavitev posameznikov, podjetij in Slovenije kot države. Ker gredo poročila s kongresov SITHOK široko v svet, bi to v prihodnje morala biti ena glavnih manifestacij za promocijo stroke doma in v svetu.

SITHOK 4 je bila mednarodna prireditev, na katero so poslali svoje prispevke avtorji iz 13 držav. Mednarodni in domači recenzenti so pregledali prispevke in jih po strogih merilih, ki veljajo za prireditve IIR razporedili v posamezne skupine. Ker je stroka KGH predvsem aplikativna, je seveda težko ločevati izvirne prispevke v stroki med znanstvene in strokovne. Odločili smo se, da so novosti v sistemskih rešitvah in nove tehnologije vendar prispevek k znanju na tem področju. Seveda pa rutinske rešitve sodijo v stroko.

SITHOK 4 – 2000 was the fourth annual international congress held by the Slovenian Association of Heating, Cooling and Air-Conditioning Engineers (SITHOK). For the first time, this congress was organised as a biennial event. During the period between the two congresses, SITHOK became an active member of REHVA, the European Federation of Heating, Ventilation and Air-Conditioning Associations. Through its representatives, it participates in the planning of its developmental strategy, the designing of university curricula and the publication of a new scientific review. For the first time this year, the International Institute for Cooling was a sponsor and included SITHOK 4 in its annual list of events. Constant participation by reputed foreign researchers and professionals from Europe and the USA proves that Slovenia, in spite of its small size, is a recognised partner in the international community. This is important not only for SITHOK members, but primarily for Slovene industry in this field.

Slovene engineers, predominantly members of SITHOK and also of the Chamber of Engineers, prove their high level of professional competence and international competitiveness through their projects. Unfortunately, they have been unable to present their achievements to the Slovene and international professional public, often because there is not enough time or support for this from the managerial staff in their companies. However, we must be aware that only the public presentation of achievements will enable the wider international establishment of individuals, companies and Slovenia as a country. Since reports from SITHOK congresses are circulated all over the world, it is expected to be one of the main events for the promotion of this field in the future, both in Slovenia and abroad.

SITHOK 4 was an international congress which featured papers by authors from 13 countries. International and Slovene reviewers studied the papers and classified them into individual groups according to the strict criteria which apply to IIR events. Since the field of heating, cooling and air-conditioning (HCA) is primarily an applied field, it is naturally difficult to classify the original contributions as either scientific or professional. It was decided that new achievements in systems solutions and new technologies are nevertheless a contribution to the knowledge in this field. Naturally, routine solutions are part of the professional work.

Stroka KGH je pred veliko odgovornostjo pri reševanju emisije toplogrednih plinov in ozonske plasti. Naprave za ogrevanje in hlajenje lahko bistveno zmanjšajo te emisije. Ozonska plast bo, z zamenjavo hladiv, upajmo, kmalu rešena. Uporaba naravnih hladiv je v Sloveniji dobila močan poudarek pri gradnji gospodinjskih aparatov. Naša naloga je, da jih vpeljemo tudi na področje klimatizacije.

Premišljena raba energije za ogrevanje in prezračevanje bo z novimi predpisi dobila poseben poudarek. Več ko 30% slovenske primarne energije "pokurimo" za ogrevanje stavb. Ureditev starih instalacij z zamenjavo kotlov in prenosnikov toplote ter vgradnjo sodobne mikroprocesorske regulacije naj bi bila ena glavnih nalog v naslednjem obdobju. Že samo s temi ukrepi lahko prihranimo več ko 5% primarne energije. Preostalih 10 odstotkov pričakovanih prihrankov pa bo seveda treba pokriti z boljšo izolacijo objektov. Številka v odstotkih ni velika, toda to pomeni prihranek okoli 13 PJ/leto. Pri 1500 urah obratovanja to pomeni moč 2400 MW, kar je skoraj enakovredno instalirani moči slovenskih elektrarn.

Prepričan sem, da je prav zaradi premajhne seznanjenosti širše javnosti o naših aktivnostih in možnostih krivo, da stroka KGH, v primerjavi z drugimi, nima tako uglednega mesta. Naj ti razširjeni številki SV (7 in 8) opozorita strokovno in drugo javnost na pomen stroke KGH za učinkovito rabo energije, kakovost življenja in varstvo okolja.

Dokler bo človeštvo obstajalo, bo potrebovalo ogrevane, prezračevane in po potrebi hlajene delovne in bivalne prostore, toplo sanitarno vodo in svetlobo. Zato raziskovalno in razvojno delo, projektiranje naprav in njihova proizvodnja na tem, interdisciplinarnem področju, niso muhe enodnevnice, niso produkti potrošniške družbe, ampak temelj, na katerem lahko gradimo naš nadaljnji razvoj.

prof.dr. Peter Novak

The profession of heating, cooling and air-conditioning (HCA) is facing the enormous task of solving the problem of emissions of greenhouse gases and the ozone layer. Heating and cooling devices can considerably reduce such emissions. Hopefully, the ozone layer problem will be solved soon with the replacement of refrigerants. The use of natural refrigerants has already become highly popular in Slovenia in the design of household appliances. It is our task to now introduce them to the field of air-conditioning.

With the adoption of the new regulations, the rational use of energy for heating and cooling will be given special emphasis. Over 30% of Slovenia's primary energy is used to heat buildings. The renovation of old systems with the replacement of boilers and heat exchangers and the installation of modern microprocessor control is expected to be one of the main tasks in the coming period. Such measures alone can save over 5% of primary energy. The remaining 10% of the expected savings will have to be achieved through better insulation of buildings. The percentage is not high, but it means savings of about 13 PJ/year. For 1500 hours of operation, this is 2400 MW of power, which is almost equal to the total installed power of all Slovene power plants.

I am sure that the HCA profession's not having the best reputation is due only to the general public's lack of information about our activities and potentials. Let this extended issues of the Journal of Mechanical Engineering (7 and 8) draw the attention of the professional and general public to the significance of the HCA profession in the efficient use of energy, the quality of life and environmental protection.

As long as humanity exists, people will need heated, ventilated and, when necessary, cooled working and residential spaces, clean hot water and lighting. Therefore, the research and developmental work as well as equipment engineering and manufacturing in this interdisciplinary field are not this month's fad or products of the consumer society, but foundations on which we can base our further development.

Prof.Dr. Peter Novak

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Optimiranje ravnega sončnega sprejemnika z nepremičnim zrcalom

The Optimization of a Solar Collector of the Flat-Thin Box Type with a Fixed Reflector

Ha Dang Trung - Nguyen Quan

Pri raziskavi novega tipa sončnega sprejemnika je bilo uporabljeno zrcalo nepremičnega tipa. Sprejemnik in zrcalo sta utrjena, tako je količina absorbirane sončne energije odvisna predvsem od kota sončnih žarkov ter razporeditve sprejemnik – zrcalo. Visoko temperaturo vode in največje absorbirano sevanje tako dosežemo z optimalno postavitvijo sprejemnika in zrcala. Raziskave so pokazale, da je primerno razmerje izmer od 1,7 do 3 (da dobimo od 33% do 38% več neposrednega sevanja). Prvotni rezultati pri preskusu ravnega sprejemnika sončnega sevanja, ki je imel površino 3,9 m² in zrcalo enake površine, so bili spodbudni.

Ta model sončnega sprejemnika je preprostejši in bolj učinkovit v območjih zmernega sončnega sevanja in uporaben za absorpcijski hladilni krog.

(Ključne besede: sprejemniki sončni, absorpcija energije, optimiranje, preskušanje)

A new design of solar collector has been investigated which uses a reflector of the fixed type. Both collector and mirror are of the non-tracking type, so the absorbed solar energy depends on the incident angle of the solar beam and the collector-mirror arrangement. A high water temperature and a maximum in the absorbed radiation can be reached by selecting an optimal dimension ratio for the collector and reflector. The research has shown that reasonable dimension ratio of 1.7 to 3 can result in 33% to 38% more direct radiation. A flat-thin box type collector of 3.9 m² with a mirror of the same area has been tested and some initial results look promising.

This model of solar collector is simpler and more efficient in regions of moderate solar radiation and useful for the absorption-refrigeration cycle.

(Keywords: solar collector, absorbed energy, optimization, testing)

0 UVOD

Uporaba kombinacije sprejemnik – zrcalo je bila omenjena v nekaterih projektih in raziskavah. Za pridobitev čim več sončnega sevanja je pomembno razmerje izmer zrcala in sprejemnika ter površina sprejemnika. Za okrogel ploščat sprejemnik brez zrcala ali zgoščevalnika premičnega tipa je absorbirana sončna energija odvisna od površine sprejemnika. To pomeni, da imajo različni sprejemniki enake površine enako zmožnost absorpcije, čeprav se njihova razmerja izmer razlikujejo. Za kombinacijo sprejemnik – zrcalo nepremičnega tipa pa je vse skupaj bolj zapleteno. Absorbirana sončna energija, ki vključuje odbojno sevanje, je odvisna od razmerja izmer in spremembe kota sončnih žarkov.

0 INTRODUCTION

Using a collector-reflector combination as a solar collector has been mentioned in some projects and researches, but the dimensional relationship of the reflector and collector is often based on the collector's area to obtain the determined solar radiation and taken qualitatively. For the flat-plate collector without reflector or concentration collector of the tracking type, absorbed solar energy depends on the collector area, not on its dimension ratio. This means the different collectors of the same area have the same capacity while their dimension ratios are not the same. But for the collector-reflector combination of the fixed type, the problem is more complicated. Absorbed solar energy, which includes the reflection radiation, depends on the dimensional relationship with the change of incident angle of the solar beam.

Pri optimiranju sprejemnikov sončne energije naletimo na problem, kako narediti kombinacijo sprejemnik – zrcalo preprosto za izdelovanje, uporabo in vzdrževanje, cenovno ugodno in energijsko učinkovito. Za izpolnitev teh pogojev je bil oblikovan in testiran model sončnega sprejemnika z nepremičnim zrcalom.

For the optimization of a solar collector, the problem is how to make the solar collector-reflector combination simple to manufacture, convenient to operate and maintain, cheap to produce while offering improved energy efficiency. To meet these requirements, a model of a solar collector with a fixed-type reflection mirror has been designed and tested.

1 ODVISNOST ABSORBIRANE ENERGIJE OD IZMER SPREJEMNIK – ZRCALO

1 DEPENDANCE OF ABSORBED ENERGY ON THE COLLECTOR-MIRROR DIMENSIONS

Absorbirano energijo, ki jo sprejme okrogli ploščati sprejemnik z nepremičnim zrcalom določimo [1] iz obrazca:

Useful absorbed energy for a flat-plate collector with a fixed type mirror [1] is defined by:

$$\mathrm{d}Q_u = A_c\left[F_r(\tau\alpha)(I_T + f_A I_R)\right]\mathrm{d}\omega \qquad (1)$$

kjer je:
Q_u – absorbirana energija v J
A_c – površina ravnega okroglega sprejemnika v m^2
F_R – količnik prenosa toplote
$(\tau\alpha)$ – zmnožek transmisivnosti in absorptivnosti
I_T – celotno sevanje v W/m^2
I_R – odbojno sevanje ogledala v W/m^2
ω – časovni korak, ki ustreza sončnemu urnemu kotu v s
$f_A = A_R/A_C$ – razmerje površin
A_R – površina sprejemnika, ki zbira odbojno sevanje ogledala v m^2

V primeru, ko sta površini sprejemnika in zrcala enaki in je kot med ploskvama 120°, potem je f_A = 1, če je ploskev sprejemnika vedno navpična glede na sončne žarke (premični tip). Pri nepremičnem tipu je f_A odvisen od kota sončnih žarkov (θ), kakor tudi od razmerja izmer sprejemnika L = a/b (a,b dolžina/višina sprejemnika).

Ugotovljeno je, da neposredno in razpršeno sevanje površine sprejemnika ni odvisno od f_A. Največji problem je določitev razmerja med f_A in odbojnim sevanjem I_R in potem določitev največje absorbirane energije sprejemnika [2].

where:
Q_u – useful absorbed energy, J
A_C – surface area of the flat-plate collector, m^2
F_R – heat-removal coefficient
$(\tau\alpha)$ – transmittance-absorptance product
I_T – global radiation, W/m^2
I_R – reflection radiation from the mirror, W/m^2
ω – time interval corresponding to hour angle, sec.
$f_A = A_R/A_C$ - area ratio
A_R – area proportion of the collector receiving reflection radiation from the mirror, m^2

In the case when the areas of the collector and mirror are the same and the angle between their planes is 120°, f_A = 1 if the collector's plane is always perpendicular to the solar beam (tracking type). For the non-tracking type, f_A depends on the incident angle of the solar beam (θ) as well as the dimension ratio of the collector, L = a/b (a and b are the length and the width of the collector, respectively).

It is recommended that the direct and diffusion radiation which is incident on the collector's surface does not depend on f_A. So the important problem is how to determine the relation between f_A and the reflection radiation (I_R), and then to determine the maximum absorbed energy of the collector [2].

$$f_A = \left|1 - \frac{\sqrt{3}}{2L} tg\theta\right|$$

če je $|\theta| \le \arctan L/\sqrt{3}$ — when $|\theta| \le \arctan L/\sqrt{3}$

$$\left|\frac{L}{2\sqrt{3}} c\tan\theta\right| \qquad (2)$$

če je $|\theta| > \arctan L/\sqrt{3}$ — when $|\theta| > \arctan L/\sqrt{3}$

S kombinacijo enačb (1) in (2) ter upoštevanjem, daje $I_R = \mu I_b \cos\theta/2$, kjer μ pomeni zrcalno odbojnost in I_b neposredno sevanje, dobimo:

Combining eqs. (1) and (2), and with the knowledge that $I_R = \mu I_b \cos\theta/2$, where μ is the mirror's reflectance and I_b is the direct radiation, we have:

$$\mathrm{d}Q_u = \left[A_C F_R(\tau\alpha) I_T + \mu A_C F_R(\tau\alpha) f_A I_b \frac{\cos\theta}{2}\right]\mathrm{d}\omega \qquad (3).$$

Pri izračunu ločimo sprejeto in odbito sevanje $\mathrm{d}Q_C$ in $\mathrm{d}Q_R$:

For convenience, the collector's radiation and the reflection radiation can be separated as $\mathrm{d}Q_C$ and $\mathrm{d}Q_R$, respectively:

$$\mathrm{d}Q_R = \mu A_C F_R(\tau\alpha) f_A I_b \frac{\cos\theta}{2}\mathrm{d}\omega \quad (4)$$

Ker je razmerje med sončnim urnim kotom ω in kotom sončnih žarkov θ sorazmerno s sončnim gibanjem, je simetrično s ploskvijo sprejemnika (pred sončnim poldnevom in po njem):

Because the relation between the hour angle (ω) and the incident angle (θ) is linear and the sun's movement is symmetrical to the collector's plane (before and after solar noon):

$$\theta = \frac{\pi}{2}\frac{\omega}{\Delta\omega} \quad \text{ali/or} \quad \mathrm{d}\omega = 2\frac{\Delta\omega}{\pi}\mathrm{d}\theta \quad (5)$$

Če vstavimo $B = L/\sqrt{3}$ in integriramo (4), dobimo:

Put $B = L/\sqrt{3}$ and taking the integral for (4) we have:

$$Q_R = \frac{\Delta\omega}{\pi}\mu A_C F_R(\tau\alpha) I_b \left(-B\ln\left|\frac{1}{B}\left(\sqrt{1+B^2}-1\right)\right| + \frac{1}{B}\left(\sqrt{1+B^2}-1\right)\right) \quad (6)$$

podobno:

similary:

$$Q_C = 4\frac{\Delta\omega}{\pi} A_C F_R(\tau\alpha) I_b + 2\Delta\omega A_C F_R(\tau\alpha) I_d \quad (7).$$

Prvi del enačbe pomeni neposredno sevanje Q_{Cb}, drugi del pa razpršeno sevanje Q_{Cd}.

Ugotovljeno je bilo, da je Q_R zelo odvisen od parametera B, oziroma od razmerja L. Iz tega izhaja, da izbira razmerja dimenzij L vpliva na količino absorbirane energije in s tem na učinkovitost sprejemnika.

Določitev razmerja $Q_R/Q_{Cb} = f_B$, ki je funkcija B v %

The first term of eq. (7) is the direct radiation energy (Q_{Cb}) and the second term is the diffusion energy (Q_{Cd}).

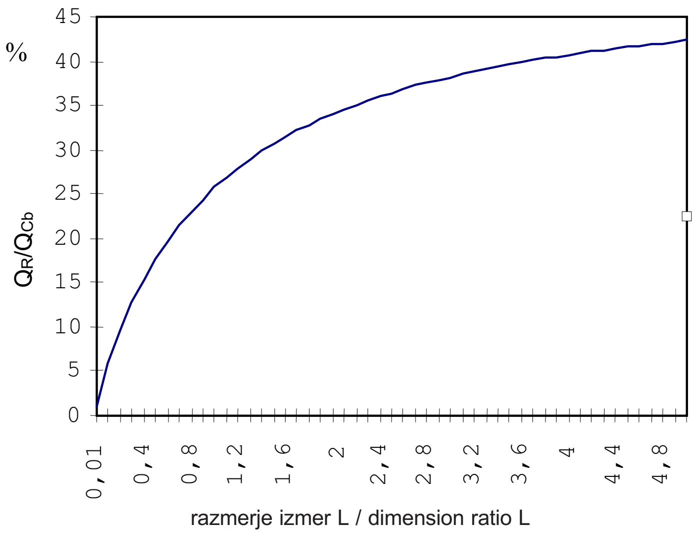
It is recommended that Q_R depends very much on the parameter B, i.e on the ratio L. So the selection of the dimension ratio L would affect the absorbed energy and the efficiency of the collector.

Symbolizing the ratio Q_R/Q_{Cb} to be f_B as a function of B, %

$$f_B = Q_R/Q_{Cb} = \frac{\mu}{4}\left(-B\ln\left|\frac{1}{B}\left(\sqrt{1+B^2}-1\right)\right| + \frac{1}{B}\left(\sqrt{1+B^2}-1\right)\right) \quad (8)$$

in predstavitev razmerja med f_B in L na sliki 1. Iz tega lahko vidimo sprejemljivo razmerje, da pri L = 1,7 do 3 dobimo 32% do 38% več neposrednega sevanja (z uporabo močno odbojnega stekla zrcala, $\mu \approx 1$).

and expressing the relation between f_B and L in Fig. 1, it can be seen that a reasonable ratio of L = 1.7 to 3 will result in 32% to 38% more direct radiation (when a glass mirror of high reflectance is used, i.e $\mu \approx 1$).



Sl. 1. *Razmerje med f_B in L*
Fig. 1. *Relation between f_B and L*

2 OPTIMIRANJE IZMER SPREJEMNIK – ZRCALO

Za določitev optimalnega razmerja L za kombinacijo sprejemnik – zrcalo moramo upoštevati stroške porabe energije in izdelave sprejemnika.

Z uporabo odbojnega zrcala so povprečni mesečni stroški za električno energijo E družine nižji. Zmanjšanje stroškov ΔE je posledica razmerja izmer L, kar je razvidno iz funkcije Q_R.

2 OPTIMIZATION OF THE COLLECTOR-MIRROR DIMENSIONS

To fully evaluate an optimal ratio of L for the collector-reflector combination, the cost of energy consumption and collector manufacturing should be included.

Using a reflection mirror can make the monthly average expenditure on electrical consumption (E) for a family lower and the dependence of the expenditure reduction (ΔE) on the dimension ratio (L) is a function of Q_R.

$$\Delta E = 30 \cdot 10^{-6} p Q_R \quad \text{USD/mesec} \quad \text{USD/month} \tag{9}$$

kjer so:
Q_R – absorbirana odbojna energija v J
p – cena energije na enoto, VND/MJ
30 – povprečno št. dni v mesecu
Tako znašajo mesečni stroški:

where :
Q_R – useful energy absorbed from the reflection radiation, J
p – power unit price, VND/ MJ
30 – average days per month
So, actual monthly expenditure will be :

$$Ea = E - \Delta E \quad \text{USD/mesec} \quad \text{USD/month} \tag{10}$$

Stroški sistema C kombinacije sprejemnik – zrcalo se linearno zvečuje z L, in so določeni tudi z dobo trajanja [3]. Predpostavljamo, da je doba trajanja sistema 5 in 10 let:

The installation cost (C) of a collector-reflector combination is linearly proportional to L and determined by different life-times of the combination [3]. Assuming the life-time of the equipment to be 5 and 10 years:

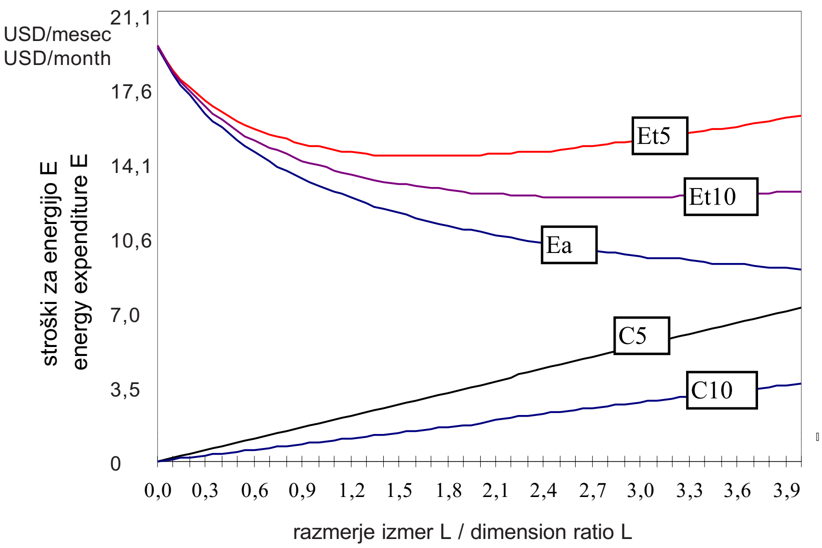
$$C = P\frac{i(1+i)^n}{(1+i)^n - 1}L, \quad \text{USD/mesec} \quad \text{USD/month} \tag{11}$$

kjer so:
P – stroški sprejemnik – zrcalo v USD/m^2
i – mesečna obrestna mera v %
n – doba trajanja v mesecih, 60 ali 120 mesecev

Slika 2 prikazuje odvisnost E_a in C od razmerja dimenzij L pa tudi celotne stroške L $E_t = (E_a + C)$, kjer so E_{t5}, E_{t10} in C_5, C_{10} vrednosti E_t in C za 5 in 10 let dobe trajanja.

where:
P – collector-reflector cost, USD/m^2
i – monthly interest rate, %
n – months of life-time, 60 or 120 months

Figure 2 shows the dependence of E_a and C on the dimension ratio (L), as well as the total expenditure $E_t = (E_a + C)$ on L, in which E_{t5}, E_{t10} and C_5, C_{10} are the values of E_t and C for 5 and 10 years of life-time, respectively.



Sl. 2. *Stroški energije E_t v odvisnosti od razmerja izmer*
Fig. 2. *Energy Expenditure (E_t) vs Dimension Ratio L*

Jasno je, da dosežejo povprečni mesečni stroški za energijo najmanjšo vrednost takrat, kadar je L = 1,7 do 3 (kar ustreza dobi trajanja sprejemnika 5 ali 10 let). To vrednost razmerja izmer svetujejo za uporabo načrtovanja in izdelave sončnih sprejemnikov v Vietnamu (in morda tudi v drugih manj razvitih državah).

It is clear that the monthly average expenditure for energy consumption is a minimum value in the interval of L = 1.7 to 3 (corresponding to a life-time of the collector of 5 or 10 years). So this value of the dimension ratio is suggested for use when designing and manufacturing a solar collector in Vietnam (and maybe in some other less-developed countries).

3 PRESKUS SPREJEMNIKOV RAZLIČNIH RAZMERIJ IZMER

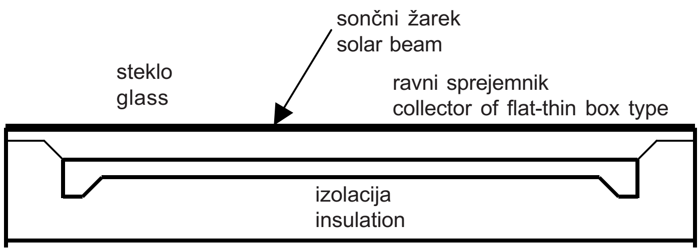
3 TESTING A COLLECTOR OF DIFFERENT DIMENSION RATIOS

Proučevali so kombinacijo sprejemnik – zrcalo. Sestavljeno je iz treh ploščatih sprejemnikov dimenzij 1,0 x 1,3 m in treh zrcal enakih izmer (razmerja izmer L_1 = 0,77, L_2 = 1,54, L_3 = 2,31). Ta sestav sprejemnika je prikazan na sliki 3.

Raziskovalno delo temelji na učinkovitosti in energijski enačbi sprejemnika [1]:

A collector-reflector combination has been investigated. It has 3 flat-plate collectors of 1.0 x 1.3 m with 3 mirrors of the same dimension (dimension ratios L_1 = 0.77, L_2 = 1.54, L_3 = 2.31). The collector structure is shown in Fig.3.

The experimental work is based on the efficiency expression and energy equation of the collector [1]:



Sl. 3. *Struktura sprejemnika*
Fig.3. *The collector structure*

$$\eta_i = \frac{Q_u}{A_C I_T} = F_R(\tau\alpha) - F_R U_L \frac{T_i - T_a}{I_T} \quad (12)$$

in / and

$$Q_U = mC_p(T_0 - T_i) \quad (13),$$

kjer so T_i, T_0, T_a: vstopna, izstopna temperatura delovnega fluida in temperatura okolja, C_p specifična toplota vode v J/kgK.

Strukturni parametri sprejemnika so naslednji:

- izmere ploščatega sprejemnika: L x W x D = 1220 mm x 920 mm x 5 mm
- izmere posameznega sprejemnika: L x W x D = 1300 mm x 1000 mm x 100 mm
- količina vode v posameznem sprejemniku: 5,98kg
- debelina stekla: 3 mm
- prostor med steklom in ploščato površino: 35 mm
- material absorberja: galvanizirana plošča: 0,8 mm (brez selektivnega nanosa).

where T_i, T_o, T_a are the outlet and inlet temperature of the working fluid and the ambient temperature, respectively. C_p is the specific heat capacity of water, J/kg.K.

The structural parameters of the collector are as follows:

- dimensions of flat-thin box: L x W x D = 1220 mm x 920 mm x 5 mm
- packaged dimensions of collector unit: L x W x D = 1300 mm x 1000 mm x 100 mm
- water weight of collector unit: 5.98 kg
- glass thickness: 3 mm
- space between the glass and the flat-thin box surface: 35 mm
- flat-thin box material: galvanized sheet 0.8 mm (no selective coating).

3.1 Določitev značilnih parametrov sprejemnika

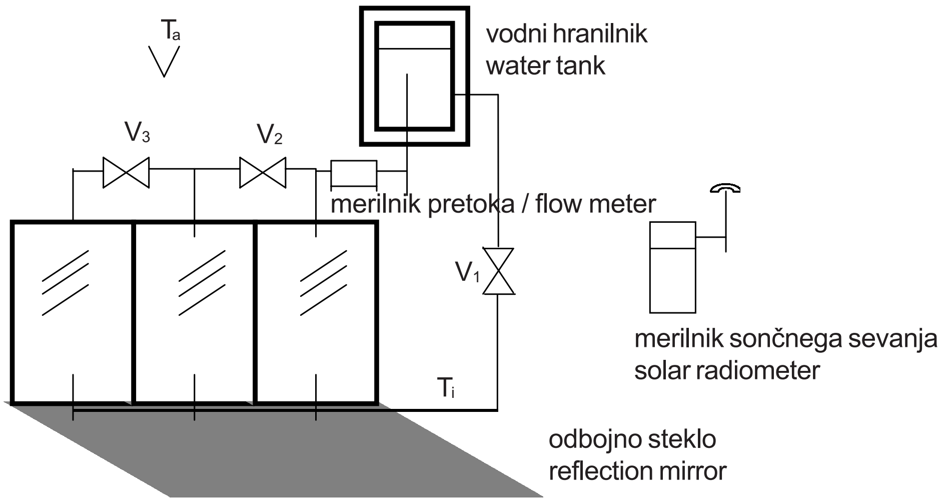
Za preskus so potrebni naslednji podatki:

- celotno sončno sevanje I_T v W/m^2
- celotna sončna energija Q_T v J/m^2
- vstopna in izstopna temperatura vode T_{fi} in T_{fo} v K

3.1 Determining characteristic parameters of the collector :

Experiment data required :

- global solar radiation (I_T), W/m^2
- global solar energy (Q_T), J/m^2
- inlet and outlet water temperature (T_{fi}) and (T_{fo}), K



Sl. 4. *Eksperimentalni načrt*
Fig. 4. *Experimental scheme*

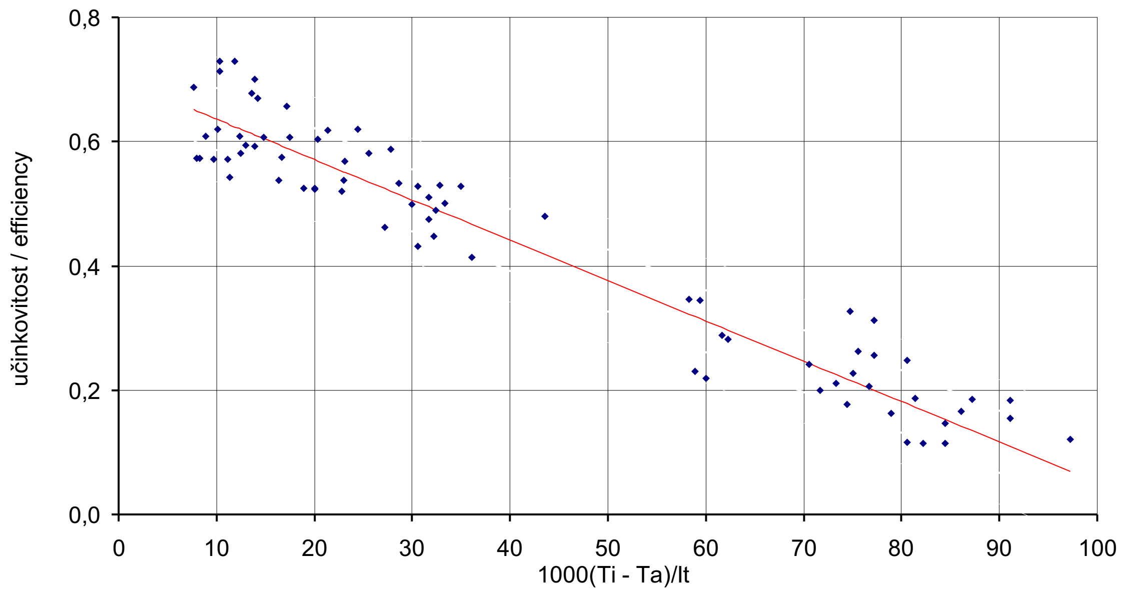
- temperatura okolja T_a v K
- masni tok vode m v kg/s.

Z uporabo enačb (12) in (13) pridemo do razmerja med učinkovitostjo sprejemnika in $(T_i - T_a)/I_T$, karakteristični parametri sprejemnika so znani (sl. 5):

- ambient temperature (T_a), K
- water flow rate (m), kg/s

Using eqs. (12) and (13) to establish the relation between the collector efficiency and $(T_i - T_a)/I_T$, the characteristic parameters of the collector can be found (Fig. 5):

$$F_R(\tau\alpha) = 0{,}708 \qquad \text{in / and} \qquad F_R U_L = 6{,}49\ \text{W/m}^2\text{K}$$



Sl. 5. *Učinkovitost sprejemnika v odvisnosti od* $(T_i - T_a)/I_T$
Fig. 5. *Collector efficiency vs* $(T_i - T_a)/I_T$

3.2 Določanje sprejemnika glede na različna razmerja izmer

Preskus je bil opravljen s tremi različnimi razmerji izmer: $L1 = 0{,}77$; $L2 = 1{,}54$; $L3 = 2{,}31$.
Potrebni eksperimentalni podatki:

- temperatura okolice T_a v K,
- povprečna temperatura vode v rezervoarju T_f in

3.2 Determining the dependance of the collector on the collector dimension ratio.

Experiments were carried out using 3 different dimension ratios : $L_1 = 0.77$; $L_2 = 1.54$ and $L_3 = 2.31$.
Experimental data equired:

- ambient temperature (T_a), K,
- average water temperature in the tank (T_f) and

vstopna temperatura vode T_i v K,
- celotno sevanje I_T v W/m² in celotna globalna energija G_T v J/m².

Energijo, ki je na voljo, določimo iz obrazca:

inlet water temperature (T_i), K,
- Global Radiation (I_T), W/m² and global radiation energy (G_T), J/m².

In this experiment, the useful energy can be calculated as:

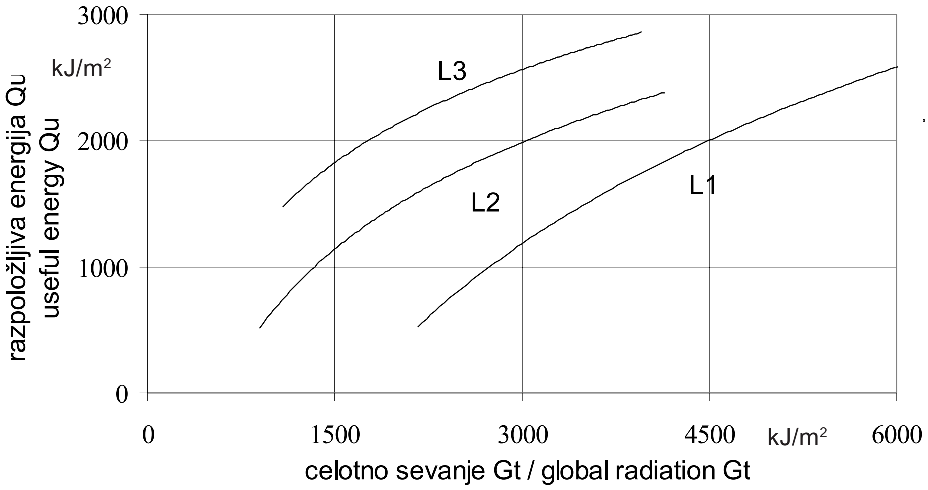
$$Q_u = MC_p(\Delta T_f) \qquad (14)$$

kjer je:
M - masa vode v sprejemniku, hranilniku in cevovodu v kg
ΔT_f - sprememba povprečne temperature v rezervoarju v K.

Odvisnost razpoložljive energije Q_u od razmerja dimenzij L in globalnega sevanja G_T je vidna na sliki 6.

where:
M - mass of water in the system of collector, water tank and connection pipe, kg
ΔT_f - average water temperature difference in the tank, K

The dependance of the useful energy (Q_u) on dimension ratio (L) and global radiation (G_T) can be seen in Fig.6.



Sl. 6. *Energija, ki je na voljo, v odvisnosti od razmerja izmer*
Fig. 6. *Useful energy of the collector with different dimension ratia*

4 SKLEP

Ravni sprejemnik sončne energije z galvanizirano ploščo ima sprejemljive značilnosti parametrov, ki so podobni cevnim, vendar so preprostejši za izdelavo in nimajo selektivnega nanosa. Z uporabo nepremičnega zrcala lahko dosežemo višjo temperaturo delovnega fluida, v dneh zmernega sevanja (pod 800 W/m²) doseže temperatura v hranilniku tudi 97 °C. Tako visoke temperature delovne tekočine so potrebne za absorpcijski hladilni krog. Z uporabo optimalnega razmerja izmer sprejemnik – zrcalo dobimo od 33 do 38% več neposrednega sevanja in večjo učinkovitost (glej sliko 1 in podatke spodaj).

4 CONCLUSIONS

The solar collector of the flat-thin box type made of galvanized sheet has acceptable characteristic parameters, which are similar to that of the tube-sheet type of collector but it is simpler to fabricate and has no selective coating. Using a fixed reflection mirror can make the temperature of the working fluid higher: on days of moderate radiation (below 800 W/m²), the water temperature in the tank could reach 97°C. Such a high temperature of the working fluid is necessary for the absorption-refrigeration cycle. By taking an optimal dimension ratio for the collector-reflector design it is possible to get 33% to 38% more direct radiation as well as higher efficiency (see Fig.1 and the data below).

L	0,77	1,54	2,31
$F_R(\tau\alpha)$	0,737	0,7545	0,7679
$F_R U_L$, W/m²K	6,9332	6,7907	6,543
η_{av}, %	19,3	36,5	57

Ta model kombinacije sprejemnik – zrcalo je uporaben v nekaterih tropskih državah za razvoj vodnega sončnega ogrevanja (VSO - SWH) ali sončnega absorpcijskega hlajenja (SOH - SAR).

So this design of the collector-reflector combination may be used in some tropical countries to develop a solar water heater (SWH) or a solar absorption refrigerator (SAR).

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Kakovosten zrak v pisarnah povečuje produktivnost

Good Air Quality in Offices Improves Productivity

P. Ole Fanger

Tri nedavne neodvisne študije so pokazale, da ima kakovost zraka v pisarnah pomemben in pozitiven vpliv na produktivnost zaposlenih. Kombinacije analiz rezultatov raziskav kažejo pomembno povezavo med produktivnostjo in kakovostjo zraka. Z izboljšanjem kakovosti zraka v pisarni se zvečuje produktivnost. Ena od možnosti zagotavljanja kakovostnega zraka za dihanje ljudi, brez pretirane ventilacije in porabe energije, je zagotavljanje ˝osebnega zraka˝ vsakemu posamezniku. O tej temi piše ta prispevek.

(Ključne besede: zrak v prostorih, vplivi na produktivnost, ventilacija, kakovost zraka)

Three recent independent studies have documented that the quality of indoor air has a significant and positive influence on the productivity of office workers. A combined analysis of the results of the three studies shows a significant relationship between productivity and perceived indoor air quality. The impact on productivity justifies a much higher indoor air quality than the minimum levels prescribed in present standards and guidelines. One way of providing air of high quality for people to breathe, without involving excessive ventilation rates and energy use, is to provide "personalized air" to each individual.The application of this concept is discussed in this paper.

(Keywords: indoor air quality, productivity, ventilation, personalized air)

0 UVOD

Yagou je leta 1936 predstavil novo filozofijo prezračevanja z namenom zagotoviti notranjo kakovost zraka ljudem. Ta filozofija je podlaga za prezračevalne standarde neindustrijskih poslopij. Na tej podlagi so bili nedavno sprejeti tudi standardi in priporočila, to so ASHRAE Standard 62 [1] in CR 1752 [2]. Kakovost notranjega zraka ima zelo velik vpliv na ljudi. Tri nedavne študije so pokazale, da ima kakovost zraka v pisarnah pomemben vpliv na produktivnost in simptome nezdravih prostorov (SNP - SBS). Te študije so prikazane v prvem odstavku tega članka.

Dobro kakovost zraka v prostoru lahko dosežemo z zmanjševanjem virov onesnaženja, povečanjem stopnje prezračevanja ali s čiščenjem zraka. Pomembna je vrednost zraka, ki ga uslužbenci dihajo. Ena izmed možnosti je dovod zelo dobrega zraka v območje dihanja vsakega posameznika. Drugi odstavek tega članka govori o ˝osebnem zraku˝.

0 INTRODUCTION

In 1936, Yagou introduced a new philosophy for ventilation, the aim being to provide an indoor air quality that is perceived as acceptable by people. This philosophy has subsequently dominated the thinking in ventilation standards for nonindustrial buildings. It is still the idea behind recent standards and guidelines such as the ASHRAE Standard 62 [1] and the recent CR 1752 [2]. But indoor air quality has an impact on humans beyond perception. Three recent studies have now documented that indoor air quality has a significant impact on productivity in offices and on sick building syndrome (SBS) symptoms. These studies are reviewed in the first section of this paper.

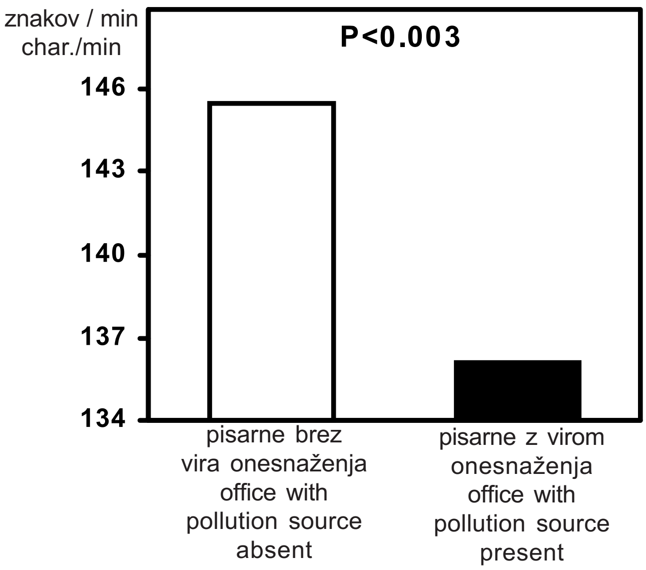
High air quality in a space can be achieved by decreasing the pollution sources, by increasing the ventilation rate, or by cleaning the air. But what really counts is the quality of the air that the occupants breathe. One option is to supply air of high quality direct to the breathing zone of each individual. The establishment of such "personalized air" is discussed in the second section of this paper.

1 PRODUKTIVNOST IN NOTRANJA KAKOVOST ZRAKA

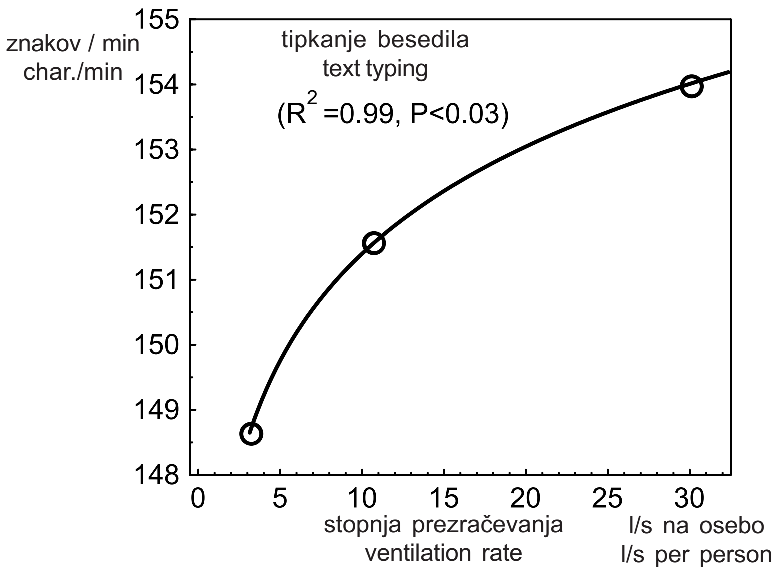
Tri nedavne neodvisne študije kažejo, da ima kakovost notranjega zraka pomemben in pozitiven vpliv na produktivnost zaposlenih. V dobro nadzorovani pisarni, ki je bila namenjena za preskus, so uporabili dve različni kakovosti zraka (boljše in slabše kakovosti), za kar zaposleni niso vedeli [6]. Po evropskih priporočilih za oblikovanje notranjega okolja [2] sta dva primera ustrezala bolni in zdravi stavbi. Iste osebe - zaposleni so delali 4 do 1/2 ure pri obeh kakovostih zraka, pri tem so stopnja prezračevanja in vsi drugi dejavniki okolja ostali nespremenjeni. Ugotovljeno je bilo, da je produktivnost teh oseb večja za 6,5% ($P<0,003$) pri dobri kakovosti zraka (sl. 1) in da so naredili manj napak in doživeli manj simptomov nezdravih prostorov. Raziskava je bila opravljena na Danskem, kasneje je bila ponovljena na Švedskem, pri kateri so dobili podobne rezultate [5]. Tretja študija je bila opravljena na Danskem z enakimi viri onesnaženja pri treh različnih stopnjah prezračevanja: 3, 10 in 30 l/s na osebo. Produktivnost se je zvečala s stopnjami prezračevanja (sl. 2). Te tri študije so analizirale odvisnost produktivnosti od kakovosti zraka, zajemale so sedem različnih eksperimentalnih dejavnikov in 90 oseb in bile analizirane kot celota [8]. Rezultati so prikazani na sliki 3 in kažejo močan vpliv kakovosti zraka na produktivnost v pisarnah. Izboljšanje kakovosti zraka za 1 decipol pomeni povečanje produktivnosti za 0,5%. Rezultati študij kažejo, da večja kakovost zraka pomembno vpliva na povečanje produktivnosti.

1 PRODUCTIVITY AND INDOOR AIR QUALITY

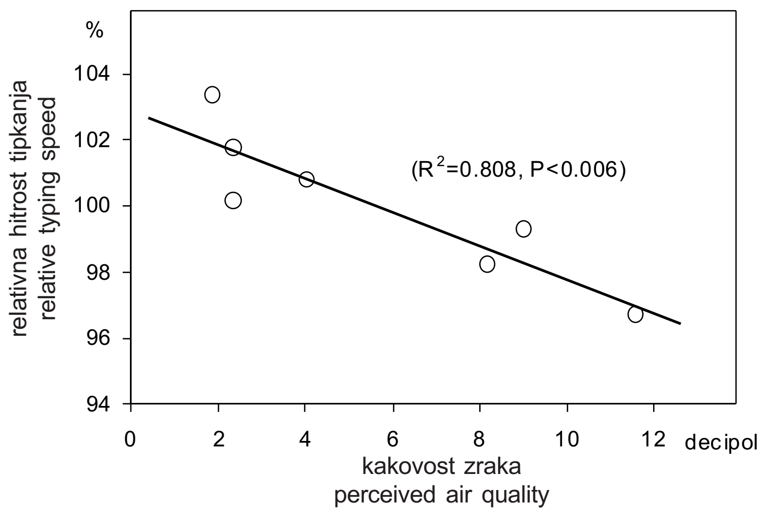
Three recent independent studies document that the quality of indoor air has a significant and positive influence on the productivity of office workers. In one study, a well-controlled normal office (field lab) was used in which two different air qualities were established by including or excluding an extra pollution source, invisible to the occupants [6]. The two cases corresponded to a low-polluting and a non-low-polluting building as specified in the new European guidelines for the design of indoor environments [2]. The same subjects worked for 4-1/2 hours on simulated office work in each of the two air qualities. The ventilation rate and all other environmental factors were the same under the two conditions. The productivity of the subjects was found to be 6.5% higher ($P<0.003$) in good air quality (Fig. 1) and they also made fewer errors and experienced fewer SBS symptoms. This study performed in Denmark was later repeated in Sweden with similar results [5]. A third study was performed in the Danish field lab with the same pollution sources present at three different ventilation rates: 3, 10 and 30 l/s×person. The productivity increased significantly with increased ventilation (Fig. 2). The three studies involving seven experimental conditions and 90 subjects have been analysed as a whole, relating productivity to perceived air quality [8]. The results are presented in Figure 3 and show a significant influence of perceived air quality on productivity in offices. An improvement of perceived air quality by 1 decipol increased productivity by 0.5%. The results of three blind studies document that improved air quality increases productivity significantly.



Sl. 1. *Vpliv notranjega onesnaženega zraka na produktivnost pri pisanju na osebni računalnik [6]*
Fig. 1. *Impact of indoor air pollution on productivity, i.e. number of characters typed on a PC [6]*



Sl. 2. *Vpliv stopnje prezarčevanja na produktivnost [7]*
Fig. 2. *Impact of ventilation rate on productivity [7]*



Sl. 3. *Razmerje med kakovostjo zraka in produktivnostjo [8]*
Fig. 3. *Relation between perceived air quality and productivity [8]*

2 OSEBNI ZRAK

Dotok svežega zraka z uporabo ventilatorjev znaša 10 l/s na osebo. Od te količine zraka se ga vdiha le 0,1 l/s na osebo oziroma 1%. Preostala količina je neuporabljena. Kako velika izguba! Pa še tisti 1% zraka, ki ga zaposleni vdihavajo, ni čist. Onesnažen je z emisijami gradbenih materialov in včasih tudi s tobačnim dimom.

Kombinirano prezračevanje naj bi zagotovilo povsem enako kakovost zraka po celotnem prostoru. To pomeni, da imajo zaposleni ne glede na to, kje so (sedijo za mizo, stojijo na mizi ali ležijo na tleh), enako kakovost zraka za dihanje.

Nadomestitev prezračevalnega sistema s kombiniranim sistemom prezarčevanja izboljšuje

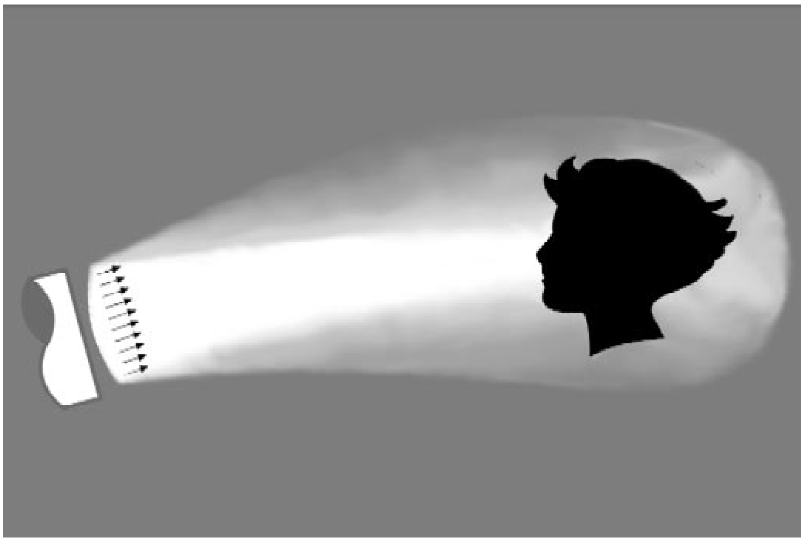
2 PERSONALIZED AIR

In many ventilated rooms the outdoor air supplied is of the order of magnitude of 10 l/s·person. Of this air, only 0.1 l/s·person, or 1%, is inhaled. The rest, i.e. 99% of the supplied air, is not used. What a huge waste! And the 1% of the ventilated air being inhaled by human occupants is not even clean. It is polluted in the space by bioeffluents, emissions from building materials and sometimes even by environmental tobacco smoke before it is inhaled.

The idea of mixing ventilation is to provide the same quality of air in the entire volume of the space. This means that occupants will find the same quality of air for breathing whether they are sitting at their desk, standing on the desk or lying on the floor.

Displacement ventilation systems do ac-kakovost zraka v dihalni coni, vendar le v majhni meri. Predvidevam, da bodo v prihodnosti uporabljeni sistemi, ki dovajajo razmeroma majhno količino čistega zraka v dihalno območje vsakega posameznika. Tako bi vsakemu zaposlenemu zagotovili dotok svežega zraka. Imeli bi pomisleke pri pitju vode, onesnažene z iztrebki. Še vedno dihamo notranji zrak, ki ga je malo prej izdihala druga oseba, in je onesnažen. Zakaj ne bi zadostovale majhne količine zelo dobrega zraka za vsakega posameznika kakor pa veliko drugorazrednega zraka v prostoru? Takšen ″osebni zrak″ (PA) bi moral biti zagotovljen tako, da bi oseba vdihavala tok svežega zraka, ki ni pomešan z onesnaženim zrakom prostora (sl. 4). V pisarnah lahko na primer postavimo ta dotok poleg računalnika na mizi. Pomembno je, da se zrak dovaja ″nežno″, tako da ima majhno hitrost in turbulenco, ki ne povzroča prepiha [3]. Z osebnim zrakom je mogoče zagotoviti zrak optimalne kakovosti. Zaposleni občutijo svež in prijeten zrak, kar ima pozitiven učinek na človeško produktivnost (sl. 3).

knowledge the air quality in the breathing zone but the ventilation effectiveness is usually only moderately better than with mixing ventilation. What I foresee in the future are systems that supply rather small quantities of clean air close to the breathing zone of each individual. The idea would be to serve to each occupant clean air that is unpolluted by the pollution sources in the space. We would hesitate to drink water from a swimming pool polluted by human bioeffluents. Still we accept consuming indoor air that has previously been in the lungs of other persons and is polluted by human bioeffluents and other contaminants generated in the space. Why not serve small quantities of high-quality air direct to each individual rather than serving plenty of mediocre air throughout the space? Such "personalized air" (PA) should be provided so that the person inhales clean air from the core of the jet where the air is unmixed with polluted room air (Fig. 4). In an office the PA may, for instance, come from an outlet next to the PC on the desk. It is essential that the air is served "gently", i.e. has a low velocity and turbulence which do not cause a draught [3]. By means of personalized air it is possible to provide breathing air of optimal quality. The air will be perceived as fresh and pleasant with a positive effect on human productivity as indicated in Fig. 3.



Sl. 4. *Načelo svežega zraka (SZ - PA): dovod majhne količine čistega zraka neposredno in blago v dihalno območje [4]*

Fig. 4. *The principle of personalized air (PA): small amounts of clean air supplied directly and gently to a person's breathing zone [4]*

V prihodnosti je izziv inženiringa za razvoj klimatizacijskih in čistilnih sistemov tak, da bo zrak optimalno kakovosten in bodo razvijali primerne metode za prenos tega zraka v dihalno območje vsakega posameznika.

The challenge for HVAC engineering in the future will be to develop conditioning and cleaning processes so that air is perceived optimally and to develop appropriate methods for transporting this air to the breathing zone of each individual without mixing with room air.

3 SKLEP

– Tri različne študije so pokazale pozitiven učinek notranje kakovosti zraka na produktivnost v pisarnah

3 CONCLUSIONS

– Three different studies have documented a positive effect of perceived indoor air quality on productivity in offices.

– Dovod osebnega zraka v dihalno območje vsakega posameznika je obetajoč osnutek, ki zagotavlja zelo dober zrak za dihanje, kar je pomembno za človeško zaznavanje in produktivnost. Priporočeno je nadaljnje delo pri teh študijah in razvijanje te zamisli.

– Personalized air supplied to the breathing zone of each individual is a promising concept, allowing a quality of the air for breathing that is optimal for human perception and productivity. Further work on studying and developing this concept is recommended.

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Dinamična analiza klimatizacijskega sistema s toplotno črpalko

Dynamic Analysis of an Air-Conditioning System with a Heat Pump

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V tem prispevku je predstavljen postopek dinamičnih analiz klimatizacijskega sistema z uporabo toplotne črpalke v odvisnosti od sprememb obratovalnih razmer skozi leto. Za ta namen so razvili nov simulirni model sistema. Model je sestavljen iz dveh povezujočih se delov: izračun toplotnih izgub oziroma toplotnih dobitkov v prostoru in določitev toplotnih in hladilnih obremenitev klimatizacijskega sistema. Na grafih so predstavljeni rezultati urnih in mesečnih porab energije za klimatizacijski sistem s toplotno črpalko, ter primerjava s standardnim osrednjim klimatizacijskim sistemom. Zaradi prilagodljivosti razvitega modela simuliranja lahko analiziramo in primerjamo različne klimatizacijske sisteme, vključno z različnimi rekuperacijskimi sistemi.

(Ključne besede: sistemi klimatizacijski, črpalke toplotne, analize dinamične, porabe energije)

In this paper a dynamic operation analysis of a low-velocity central air-conditioning system with a heat pump in terms of the changing operating conditions during the year is performed. For this purpose an original hour-by-hour simulation model of the system has been developed. The model consists of two integrated parts: calculation of the heat loss or heat gain to the space and determination of the heating and cooling load imposed on the air-conditioning system. The hourly and monthly energy use results for the air-conditioning system with heat pump, also in comparison with the standard central air-conditioning system, are presented in graphical form. Flexibility of the developed simulation model provides the possibility to analyze and compare different air-conditioning systems, including different energy-recovery systems.

(Keywords: air-conditioning systems, heat pumps, dynamic analysis, energy consumption)

0 UVOD

Zahteve po energiji in njeni porabi v klimatizacijskih sistemih imajo neposreden vpliv na obratovalne stroške stavb in posreden vpliv na okolje. Različne energijske ocenjevalne metode omogočajo kolikostne primerjave energije in stroškov različnih energijskih virov. Čeprav se postopki za ocenjevanje zahtev po energiji spreminjajo v stopnjah zahtevnosti, imajo vsi po tri skupne dele izračuna [1]:
– prostorska obremenitev
– obremenitev sekundarne opreme
– energijske zahteve primarne opreme

Sekundarni se nanaša na opremo, ki razdeljuje toploto, hlajenje ali vmesno stanje obojega v klimatizirane prostore, primaren pa se nanaša na opremo, ki spreminja gorivo ali električno energijo v hlajenje ali toploto.

V tem prispevku je poudarjena analiza obremenitve sekundarne opreme. Prvi korak je bil

0 INTRODUCTION

The energy requirements and fuel consumption of HVAC systems have a direct impact on the building operating costs and an indirect impact on the environment. Different energy estimating methods can provide quantitative energy and cost comparisons among design alternatives. Although the procedures for estimating energy requirements vary considerably in their degree of complexity, they all have three common elements of the calculation [1]:
– space load
– secondary equipment load
– primary equipment energy requirements.

Here, secondary refers to the equipment that distributes the heating, cooling or ventilating medium to the conditioned spaces and primary refers to the central plant equipment that converts fuel or electric energy to the heating or cooling effect.

In this paper, the analysis is conducted to the level of the secondary equipment load. The first določitev obremenitve prostora, ta je enak količini energije, ki mora biti dodana ali odvzeta prostoru, da ohranimo toplotno ugodje. Zahtevana energija za ohranitev ugodja je funkcija temperature zunanjega zraka, relativne vlažnosti zunanjega zraka, učinkov sonca, vetra, notranjih toplotnih dobitkov, zadrževanju toplote v elementih gradbene konstrukcije in notranjosti prostora. Naslednji korak je bila sprememba prostorske obremenitve v obremenitev sekundarne opreme. Ta korak vključuje izračun potrebne energije sekundarnega sistema, to je električne energije za delovanje ventilatorjev, črpalk in/ali kompresorjev, pa tudi energije za ogrevanje oziroma hlajenje vode. Dobljeni rezultati so podlaga za izračun zahtev po gorivu in energije primarne opreme ter nadaljnjih ekonomskih analiz klimatizacijskega sistema, ki vključujejo stroške investicije, delovanja in vzdrževanja.

1 METODA ANALIZ

Energijski izračuni prostorske obremenitve temeljijo na povprečni uporabi in tipičnih vremenskih razmerah. Na splošno najbolj pogosto predstavljeni postopki temeljijo na urnih prikazih klimatskih razmer ter številu značilnih dni v letu ali 8760 ur delovanja na leto. Izbrana metoda za izračun čistih obremenitev prostora je postopek toplotnega ravnovesja v kombinaciji z delovanjem prenosa toplote. Metoda toplotnega ravnovesja temelji na prvem zakonu termodinamike in spada k osnovnim postopkom energijske analize. Enačba toplotnega ravnovesja je napisana za vsako obdajajočo površino (stene, tla, strop in okna) in še ena za zrak prostora. Te enačbe uporabljamo za izračun neznanih temperatur in površin zraka. Ko so temperature znane, jih uporabimo za določitev toplotnega toka iz prostora ali v prostor. Predpostavljeno je, da ima pri vsakem času *t* vsaka od teh površin ter masa zraka v prostoru nespremenljivo temperaturo. V vsakem prostoru se mora vstopajoči toplotni tok izenačiti z izstopnim. Z drugimi besedami to pomeni, da je prevodni tok v ravnovesju s konvekcijo prostorskega zraka, sevanjem notranjih virov (luči, aparatov in ljudi) ter spremembo sevanja med stenami in preostalimi površinami v prostoru. Za zunanjo površino posameznega zidu je prevodni tok v ravnovesju z absorbiranim sončnim sevanjem, dolgovalovnim sevanjem iz okolja in konvekcijo zunanjega zraka. Toplotno ravnovesje mase zraka v prostoru zahteva, da klimatizacijski sistem odstrani toploto, ki je dodana masi zraka s konvekcijo notranjih površin in notranjih virov (luči, aparati in ljudje) in s prenosom snovi zaradi infiltracije.

Toplotno ravnovesje na enoto površine pri *j*-tih notranjih površinah pri času *t*, je:

step was to determine the space load, which is the amount of energy that must be added to or extracted from a space to maintain thermal comfort. The energy required to maintain comfort is a function of the outside air temperature, outside-air relative humidity, solar effects, wind effects, internal heat gains and heat storage in the building construction elements and interiors. The second step was to translate the space load to the load of secondary equipment. This step should include a calculation of the energy required by the secondary system, i.e., the electrical energy to operate fans, pumps and/or compressors as well as the energy in the form of heated or chilled water. The obtained results are prepared for use in the calculation of fuel and energy requirements by the primary equipment and in a subsequent economic analysis of an air-conditioning system, including the investment costs, operating costs and maintenance costs.

1 ANALYSIS METHOD

Energy calculations of the space load are based on average use and typical weather conditions rather than maximum use and worst-case weather. Currently, the most sophisticated procedures are based on hourly profiles for climatic conditions and operational characteristics for a number of typical days of the year or on 8760 hours of operation per year. The selected method for calculating the net-space sensible loads is the heat balance method combined with first-order conduction transfer functions. The heat balance method is based on the first law of thermodynamics and it belongs to the most fundamental energy analysis methods. Heat balance equation is written for each enclosing surface (walls, floor, ceiling and windows), plus one for the room air. This set of equations is used to calculate the unknown surface and air temperatures. Once these temperatures are known, they are used to calculate the heat flow to or from the space air mass. At any time *t*, each of these surfaces and the space air mass are assumed to be of uniform temperature. At any plane boundary, the heat flux entering the boundary must equal the heat flux leaving the boundary. In other words, at the inside surface of any room wall, the conductive flux leaving the surface is balanced by convection from the room air, radiation from interior sources (lights, machines and people) and the net radiant interchange between the wall and all the other surfaces in the room. Similarly, for the outside surface of any exterior wall, the conductive flux leaving the surface toward the room is balanced by the absorbed solar radiation, net longwave radiant flux from the surroundings and the convective flux from the outdoor air. A heat balance on the room air mass requires the air-conditioning system to remove the net heat added to the air mass by convection from interior surfaces and interior sources (lights, machines and people) and by mass transfer due to infiltration.

Thus, the heat balance per unit area at the *j*th inside surface at time *t* is:

$$q_{j,t} = \alpha_{j,t}\left(\vartheta_{a,t} - \vartheta_{SI,j,t}\right) + \sum_{k=1}^{N_S} G_{j,k}\left(\vartheta_{SI,k,t} - \vartheta_{SI,j,t}\right) + q_{RS,j,t} \tag{1}$$

kjer prvi del pomeni dobitke toplote s konvekcijo, drugi del pa spremembo dolgovalovnega sevanja med stenami in preostalimi površinami, zadnji del pa kratkovalovno sevanje luči, opreme in ljudi ter solarne dobitke skozi okna. Leva stran enačbe (1) pomeni prevod toplote homogene površine. To je predstavljeno s prejšnjimi vrednostimi temperatur površin in toplotnega toka z uporabo funkcij prevoda toplote ([2] do [4]). Funkcije prevoda toplote so v povezavi s problemom večplastnih enodimenzijskih površin:

where the first term represents the convection heat gain from the room air, the second term represents the longwave radiative interchange between the wall and all other surfaces and the last term includes shortwave radiation from lights, equipment and people and window solar gain. The left side of Eq. (1) $q_{j,t}$ must match the heat conducted into the solid surface. This is represented with historical values of surface temperatures and heat flux using conduction transfer functions ([2] to [4]). Conduction transfer functions are closely related solutions to the transient one-dimensional, multilayered-slab conduction problem:

$$q_{j,t} = \sum_{i=0}^{N} X_{j,i}\vartheta_{SI,j,t-i} - \sum_{i=0}^{N} Y_{j,i}\vartheta_{SO,j,t-i} + C_{Rj}q_{j,t-1} \tag{2}$$

Če vstavimo enačbo (2) v enačbo (1), se $q_{j,t}$ uniči. Enačbo toplotnega ravnovesja prostorskega zraka dobimo z dodatkom N_s za vse površine prostora:

By substituting Eq. (2) into Eq. (1) $q_{j,t}$ is eliminated. In addition to the N_S former equations for all room surfaces, a heat balance equation should be also written for the space air:

$$\sum_{j=1}^{N} \alpha_j A_j\left(\vartheta_{SI,j,t} - \vartheta_{a,t}\right) + m_I c_p\left(\vartheta_{o,t} - \vartheta_{a,t}\right) + \Phi_{C,t} + \Phi_{AC,t} = 0 \tag{3}$$

Prvi del pomeni konvektivni prenos s površin, drugi del prodiranje, $\Phi_{C,t}$ konvektivni prenos notranjih elementov in $\Phi_{AC,t}$ stopnjo dodane oziroma odvzete toplote s klimatizirano napravo.

Enačba (2) vključuje v drugem delu temperature zunanjih površin, ki so izražene s toplotnim ravnovesjem zunanjih površin:

Here, the first term represents the convective transfer from the enclosing surfaces, the second term represents infiltration, $\Phi_{C,t}$ convective transfer from internal objects and $\Phi_{AC,t}$ the rate of heat addition or removal by the air-conditioning equipment.

Eq. (2) in the second term involves the outside surface temperatures, which are expressed by writing a heat balance at the outside surface:

$$\sum_{i=1}^{N} Y_{j,i}\vartheta_{SI,j,t-1} - \sum_{i=0}^{N} Z_{j,i}\vartheta_{SO,j,t-i} + C_{Rj}q_{o,j,t-1} = \alpha_{o,j,t}\left(\vartheta_{SO,j,t} - \vartheta_{e,j,t}\right) \tag{4}$$

in potem vstavljene v enačbo (2). S kombinacijo enačb (2) in (4), z enačbo (1) lahko dobimo N_S+1 enačb z N_S+1 neznanih temperatur (temperature površin in temperature zraka) pri času *t*. Enačbe so urejene tako, da so vse neznanke na levi strani, znane količine pa na desni. Ta problem rešimo z uporabo stolpca - matrike. Prenos toplote na notranji strani stene je združen s prenosom toplote zunanje površine, kar pomeni funkcijo prenosa toplote za steno. Funkcija tudi združuje vse enačbe prenosa toplote notranjih sten in zaradi konvekcijskih vplivov. Tu je treba poudariti, da je za zanesljivo rešitev sistema enačb nujno treba poznati vse prej omenjene temperature in toplotne tokove.

V prejšnjih enačbah so vključene tudi klimatske razmere za območje Zagreba. Statistični algoritem uporabljamo za izbiro najbolj tipičnih mesecev iz desetletnega zapisa. Izbrani meseci pomenijo enoletne podatke o vremenu (8769 h), ki jih imenujemo značilno meteorološko leto (ZML - TMY) ali preskusno referenčno leto (PRL - TRY). Za namen analiz so potrebni naslednji podatki o vremenu: (1) temperatura zunanjega zraka, (2) relativna vlažnost

and then substituted into Eq. (2). Combining Eq. (2) and (4), with Eq. (1) represents N_S + 1 equations with N_S + 1 unknown temperatures (surface temperatures and air temperature) at time *t*. The equations are arranged so that all unknowns are on the left, and all known quantities are on the right. This enables rewriting the problem to be solved in vector-matrix notation. Through these equations, the heat transfer at an inside wall surface is coupled to the heat transfer at the outside surface by means of conduction transfer functions for the wall. It is also coupled to the heat transfer at all other surface through equations of intersurface radiation, and to the room-air volume through the convection. Here it has to be pointed out that for a successful solution of the equation system, all past temperatures and fluxes are assumed to be known.

In previous equations, climatic conditions for the Zagreb area are also included. A statistical algorithm is used to choose the most typical months from the ten–year record. The selected months present a one–year weather data set (8760 h), called a Typical Meteorological Year (TMY) or Test Reference Year (TRY). For the purpose of analysis, the following weather data are used: (1) outside air temperature, (2) zunanjega zraka, (3) sončno sevanje ter podatki o (4) vetru.

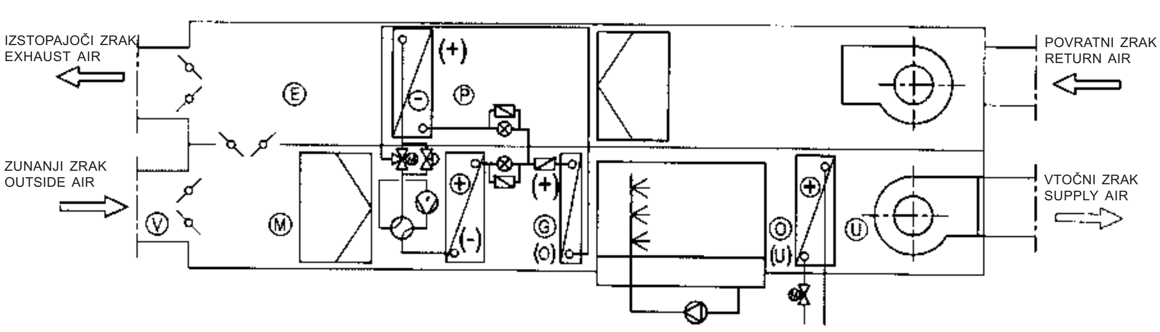
outside air relative humidity, (3) solar radiation, (4) wind data.

2 KLIMATIZACIJSKI SISTEM S TOPLOTNO ČRPALKO

2 AIR-CONDITIONING SYSTEM WITH HEAT PUMP

Področni v celoti zračni osrednji sistem s toplotno črpalko (sl. 1) je sestavljen iz naslednjih delov: (1) ventilator izstopajočega zraka, (2) filter izstopajočega zraka, (3) glušna komora, (4) dušilnik povratnega zraka, (5) dotok zunanjega zraka, (6) filter vtočnega zraka, (7) toplotna črpalka z ločenim kondenzatorjem, (8) ovlaževalnik, (9) predgrevalnik, (10) ventilator vtočnega zraka. Izbrana toplotna črpalka s spiralnim predgrevalnikom zraka lahko zamenja proces hlajenja z ogrevanjem s spreminjanjem lege ventila. V ogrevalni sezoni ima prvi prenosnik toplote vlogo kondenzatorja medtem ko ima prenosnik toplote v povratnem vodu vlogo uparjalnika. V času hlajenja prostora se stanje obrne. Prvi prenosnik deluje kot uparjalnik (hladilno navitje), drugi pa kot kondenzator. Drugi prenosnik v oskrbovalnem toku zraka ima vlogo ogrevanja zraka v hladilnem obdobju samo, ko se pojavlja kondenzacija v uparjalniku.

A single-zone, all-air, central system with heat pump (Fig. 1) is arranged with the following components: (1) return-air fan, (2) return-air filter section, (3) relief-air damper, (4) return-air damper, (5) outdoor-air intake, (6) supply-air filter section, (7) heat pump with split condenser, (8) humidifier, (9) reheat coil, (10) supply-air fan. The selected heat pump with refrigerant-to-air coils can change the cycle from the cooling to the heating mode by means of a reversing valve. So, during the heating season, the first heat exchanger in the supply air stream operates as a condenser (heater), while the heat exchanger in the return air stream operates as an evaporator. During the cooling season, the situation is reversed.The first heat exchanger in the supply air stream operates as an evaporator (cooling coil), while the heat exchanger in the return air stream operates as a condenser. The second exchanger in the air supply stream has to reheat air in the cooling season to the supply temperature, only when air dehumidification on the evaporator occurs.



Sl. 1. *Osrednji klimatizacijski sistem s toplotno črpalko*
Fig. 1. *Central air-conditioning system with heat pump*

Znaki v oklepajih na sliki 1 se nanašajo na hlajenje. Izračun za doseganje želenega termodinamičnega stanja vstopajočega zraka (določeni iz toplotnih dobitkov) sloni na tipičnem klimatizacijskem procesu: (1) ogrevanje, (2) hlajenje (z izločevalnikom vlage ali brez njega), (3) mešanje, (4) ovlaževanje.

Dodatek toplote na kondenzatorju v ogrevalni sezoni se mora ujemati s stopnjo toplote med sistemoma M in G (sl. 1) v času t:

In Fig. 1, the signs in brackets refer to the cooling operation mode. The calculation procedure used to achieve the desired thermodynamic condition of the supply air (determined from the net space load) is based on typical air-conditioning processes: (1) heating, (2) cooling (with or without moisture separation), (3) mixing, (4) moisture addition.

Heat addition from a condenser in the heating season must match the required heat rate between air conditions M and G (Fig. 1) at time t:

$$\Phi_{Co,H,t} = V_{AC,t}\rho \quad (h_{G,t} - h_{M,t}) \qquad (5),$$

kjer je entalpija zmesi $h_{M,t}$ neznana. Vrednost entalpije za standardno toplotno črpalko lahko določimo iz povezave med kapacitetama kondenzatorja in uparjalnika:

where the mixture enthalpy $h_{M,t}$ is unknown. Its value can be determined by means of the standard heat pump relation for a connection between the condenser and evaporator capacity:

$$\Phi_E = \Phi_{Co}\left(1-\frac{\eta_a}{\varepsilon_H}\right) \qquad (6),$$

kjer je:

where:

$$\varepsilon_H = \frac{\Phi_{Co}}{P_{KP}} \qquad (7).$$

Kombinacija enačb (5) in (6), skupaj z enačbo za mešanje zračnih tokov, da rešitev:

Combining Eq. (5) and Eq. (6) together with an equation for mixing of the air streams, gives the solution:

$$h_M = \frac{g_o h_V + (1-g_o)h_P - (1-g_o)\left(1-\frac{\eta_a}{\varepsilon_H}\right)h_G}{1-(1-g_o)\left(1-\frac{\eta_a}{\varepsilon_H}\right)} \qquad (8).$$

Po ovlaževanju je končno želeno toplotno razmerje doseženo z ogrevalnim navitjem (če je potrebno), s tem dosežemo primerno termodinamično stanje vstopajočega zraka:

Rest of the required heat rate is supplied by the reheat coil (if necessary), after humidification, in order to achieve an adequate thermodynamic condition of the supply air:

$$\Phi_{RH,t} = V_{AC,t}\rho \quad (h_{U,t} - h_{O,t}) \qquad (9).$$

V prehodnem obdobju med ogrevanjem in hlajenjem je primerno termodinamično stanje zraka doseženo s spreminjanjem razmerja mešanice vstopajočega in izstopajočega zračnega toka.

Če je potrebno hlajenje z ločevanjem vlage, se pojavi sprememba na toplotni črpalki. Tako prvi prenosnik vstopajočega zraka deluje kot uparjalnik, pogosto s 100% uporabo zunanjega zraka. V danem primeru je hladilna zmogljivost uparjalnika pri času *t* podana:

In the transitive period between heating and cooling seasons, adequate thermodynamic condition of the supply air is achieved by changing the mixing ratio of the return- and outside-air streams.

If air cooling is necessary, with possible moisture separation, the changeover in heat pump cycle occurs. So, the first heat exchanger in supply air stream operates as an evaporator, most often with 100% of outside air. In the former case, the cooling capacity of an evaporator at time *t* is given by:

$$\Phi_{E,t} = V_{AC,t}\rho \quad (h_{V,t} - h_{O,t}) \qquad (10).$$

Potrebna količina toplote, ki omogoča ustrezno termodinamično stanje vstopnega zraka, je lahko uporaba drugega menjalnika, ki deluje kot kondenzator. Njegova ogrevalna zmožnost se določi z enačbo (9).

The possibly required heat rate, to achieve an adequate thermodynamic condition of the supply air is supplied by a second exchanger in the supply-air stream that operates as a condenser. Its heating capacity is calculated by the term in Eq. (9).

3 REZULTATI

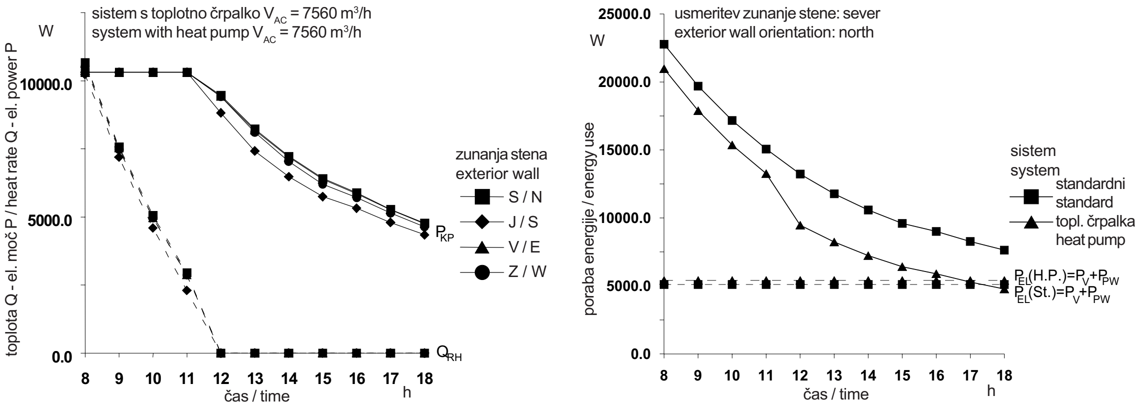
Doseženi rezultati so sestavljeni iz podatkov za 8760 h ZML. Podatki so oblikovani za vsako uro obremenitve prostora ter porabe energije posameznih komponent sistema, ki ga sestavljajo navitja, kompresor, ventilator in vodna črpalka. Poleg tega je analiziran tudi standardni osrednji klimatizacijski sistem, kjer je zahtevano ogrevanje oziroma hlajenje doseženo z ogrevanjem vode in zraka, dogrevalnim in hladilnim navitjem. Pri predstavljenih rezultatih v tem prispevku so vrednost naslednjim parametrom ne spreminja: (1) celotna prostornina prostora – 24 m x 15 m x 3,5 m, (2) celotna površina oken – 16 m^2, (3) prostornina kondenziranega zraka – 7560 m^3/h. (4) celotna notranja senzibilna toplota – 8000 W, (5) obdobje klimatizacje – 8:00 do 18:00 h.

3 RESULTS

The obtained results consist of the data sets for 8760 h of the TMY. The data sets are created for hourly net space load, and the energy use of the system components including coils, compressor, fans and water pump. In addition, analysis is also conducted for the standard central air-conditioning system, where the required heating, i.e. cooling rate is achieved by means of the water-to-air heat, reheat and cooling coils. For the results presented in this paper the following parameters are held constant: (1) total room volume – 24 m x 15 m x 3.5 m, (2) total window area – 16 m^2, (3) air-conditioning volume rate – 7560 m^3/h, (4) total internal sensible load – 8000 W, (5) system operation period – 8:00 to 18:00 h.

Na sliki 2 (levo) so rezultati urne porabe energije na karakteristični dan v ogrevalni sezoni, za sistem s toplotno črpalko. Rezultati so prikazani za vse štiri osnovne usmeritve sten skupaj. Na desni strani slike je primerjava s toplotno črpalko in standardnim sistemom, v tem primeru je uporabljena samo severna usmeritev stene.

Hourly energy use results for a characteristic day in a heating season for the system with heat pump are shown in Fig. 2 (left). The results are presented for four main exterior wall orientations, together with a comparison between the system with a heat pump and a standard system for the north-oriented room (right).



Sl. 2. *Urna poraba energije v ogrevalni sezoni*
Fig. 2. *Hourly energy use in a heating season*

Na levem diagramu (slika 2) je moč opaziti, da je najmanjša poraba energije na južni strani, najbolj neugodna pa je severna stran. To je posledica manjšega sončnega sevanja skozi steno in okna, to prispeva tudi k toplotnim dobitkom v ogrevalni sezoni. Prihranek energije pri sistemu s toplotno črpalko je pomemben v primerjavi s standardnim sistemom (sl. 2 – desni diagram). V določenih razmerah lahko razlike dosegajo tudi do 30%. Omeniti je treba, da je zaradi večjega števila navitij poraba električne energije ventilatorjev večja za sisteme s toplotno črpalko, čeprav te razlike niso tako očitne.

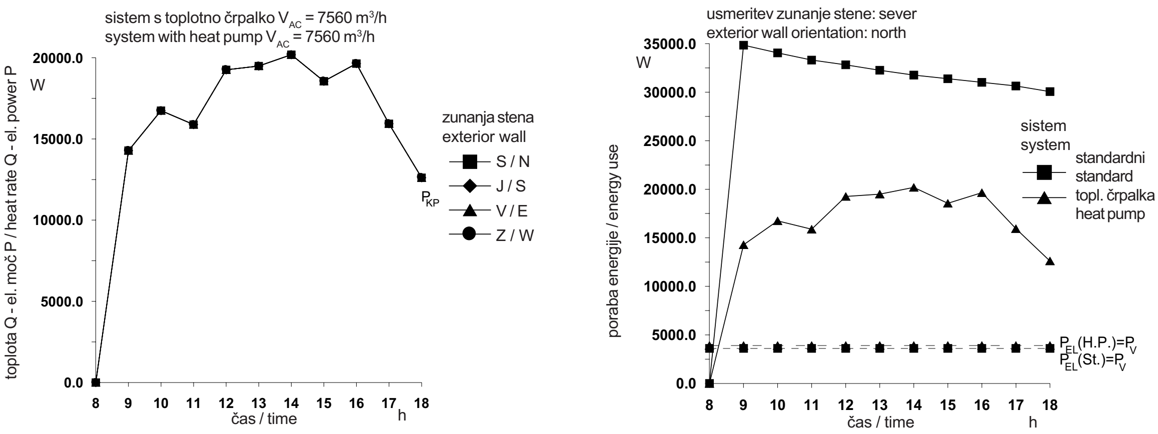
Rezultati urne porabe energije na značilni dan v hladilni sezoni, skupaj s primerjavo sistema s toplotno črpalko in običajnega sistema za severno usmeritev stene, so prikazani na sliki 3.

V urah, ko potrebujemo večje hlajenje, kompresor deluje ne glede na usmeritev prostora, ker je hlajenje naravnano na strani oddajanja toplote (sl. 3 – levo). Delovanje ogrevalnega navitja prevzema drugi prenosnik toplote v oskrbovalnem toku zraka, ki deluje kot kondenzator. Ko je potrebno manjše hlajenje, se pojavijo razlike med različno usmerjenimi površinami, posebno v zgodnjih in poznih urah delovanja sistema. Slika 3 (desno) prikazuje večje spremembe med obema analiziranima sistemoma, kakor so se pojavile med ogrevalno sezono (v določenih razmerah dosega razlika tudi vrednost 55%). Na splošno je razvidno, da so prihranki energije pri toplotni črpalki višji v obdobjih, ko je potrebno največje hlajenje. Kljub vsemu pa se le redko pojavijo tako visoke zahteve po obremenjevanju toplotne črpalke.

In the left diagram (Fig. 2) it is clear that the lowest energy use is achieved for the south orientation of a space, and the most inconvenient was the north orientation. This is the consequence of solar irradiation on the exterior wall and through the windows, which also influences the heat gain in a heating season. Energy saving with the system with a heat pump is significant compared to the standard system (Fig. 2 – right diagram). The differences can be up to 30% under certain operating conditions. Here it has to be pointed out that the electricity consumption of fans is higher for the system with a heat pump because of the higher pressure drop in the system, although this difference is not significant.

Hourly energy use results for a characteristic day in a cooling season, together with comparison between the system with a heat pump and a standard system for the north-oriented room, are presented on Fig. 3.

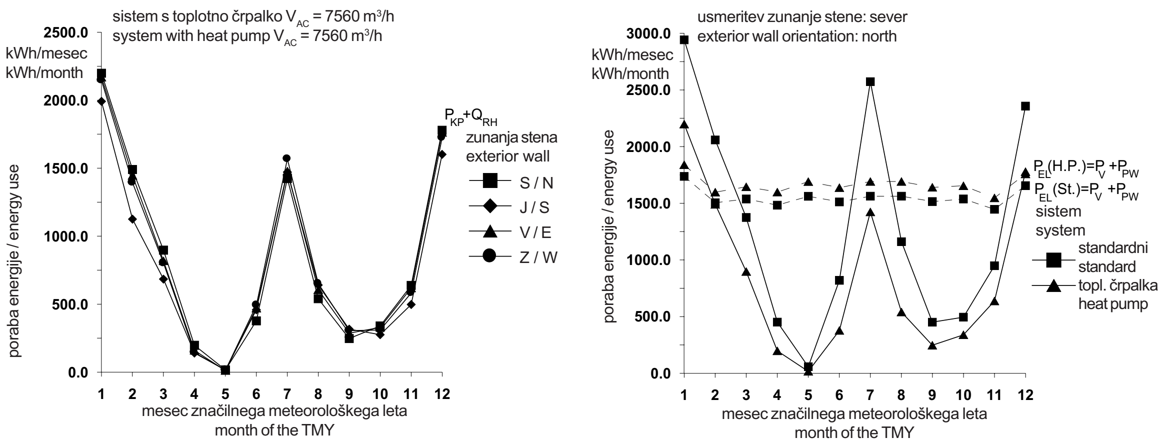
In the hours with higher required cooling rates the compressor operated regardless of the room orientation because the capacity control is done on the reheat side (Fig. 3 – left). Function of the reheat coil is taken over by the second heat pump exchanger in the supply-air stream, which operates as a condenser. When a lower cooling rate is required, there appeared some differences between the orientations, especially in the early and late operation hours. A comparison (Fig. 3 – right) showed even greater differences between the two analyzed systems than during a heating season (up to 55% under some operating conditions). Generally, it is observed that the energy saving with a heat pump is highest in the hours with maximum cooling rates. However, there are not many hours in a cooling season with such high demands on the equipment.



Sl. 3. *Urna poraba energije v hladilni sezoni*
Fig. 3. *Hourly energy use in a cooling season*

Rezultati porabe energije po posameznih mesecih skozi značilno meteorološko leto so predstavljeni na sliki 4.

Results for the energy consumption in the form of the monthly sums during the Typical Meteorological Year are presented in Fig. 4.



Sl. 4. *Poraba energije v značilnem meteorološkem letu*
Fig. 4. *Energy use during the Typical Meteorological Year*

Na levem diagramu (sl. 4) so predstavljene spremembe porabe energije za ogrevanje, hlajenje in razvlaževanje zraka v obratovalnih razmerah in za zunanjo steno. Severno usmerjeni prostori imajo večjo porabo energije v ogrevalni sezoni in manjšo v hladilni sezoni. Južno usmerjeni prostori imajo manjšo energijsko porabo v ogrevalni sezoni, zahodno usmerjeni prostori imajo večjo porabo energije v hladilni sezoni. Vsota celotne porabe energije za vse leto je največja v zahodno usmerjenih prostorih in najmanjša v južno usmerjenih prostorih. Primerjava za severno usmerjene prostore, prikazana na sliki 4 (desno), prikazuje razliko med obema analiziranima sistemoma skozi vse leto. Iz celotne vsote porabljene energije skozi vse leto je razvidno, da sistem s toplotno črpalko porabi 20% manj energije (severna stena) v primerjavi z običajnim sistemom. V določenih obdobjih hladilne sezone pa ta vrednost lahko doseže 30 odstotkov.

In the left diagram (Fig. 4) are presented the changes in energy use for heating, cooling and dehumidification of the air with operating conditions and with exterior wall orientation. The north-oriented space had the highest energy use in a heating season and the lowest energy use in a cooling season. The south-oriented space had the lowest energy use in a heating season and the west-oriented space had highest energy use in a cooling season. Total sum of the energy use for a whole year is determined to be the highest for the west-oriented space and the lowest for the south-oriented space. A comparison for the north-oriented space (Fig. 4 – right) showed differences between the two analyzed systems during a whole-year operation. The total sum for a whole year showed that the system with a heat pump consumed up to 20% less energy (north orientation), compared to the standard system. However, in some months of a cooling season this difference increased up to 30%.

4 SKLEP

Razvit vsakourni simulirni model osrednjega klimatizacijskega sistema s toplotno črpalko omogoča analizo delovanja sistema skozi različna obdobja in razmere, ki se pojavljajo med letom. Dobljeni rezultati kažejo, da ima sistem s toplotno črpalko opazno manjšo porabo energije v primerjavi z običajnim sistemom (20 do 25%, odvisno od usmeritve prostora). Zaradi navedenega je uporaba ekonomsko upravičena, vendar bi pred dejansko odločitvijo o uporabi bilo pametno upoštevati tudi stroške investicije in vzdrževanja.

Toplotna ravnovesna metoda, uporabljena za izračun ocenjenih energijskih obremenitev, je odvisna od modela, uporabljenega za oblikovanje ali izbiranje opreme, ker temelji na tipičnih vremenskih podatkih. Zaradi njenih velikih zmožnosti avtorji predpostavljajo, da se bo uporaba metode v klimatizacijskih sistemih v prihodnosti povečala. V tem trenutku je največja omejitev metode njena zapletenost, toda z razvojem in uporabo vse hitrejših računalnikov je moč upati, da bo tudi ta omejitev odpravljena.

4 CONCLUSION

The developed hour-by-hour simulation model for a central air-conditioning system with heat pump enabled a system operation analysis under different operating conditions during the year. The results showed that the system with a heat pump had significantly lower energy use compared to the standard system (20 to 25%, depending on the space orientation). Therefore, its application seems to be economically justified, although for the complete evaluation, investment and maintenance costs should be also included.

The heat balance method used for calculating the load aspects of energy estimating is different from the model used to design or select the equipment because it is based on typical weather conditions. Because of its great possibilities the authors presume that its use for the HVAC system operation analysis will increase in the future. The most limiting factor at the moment is its complexity, but fast computer development could create the prerequisite conditions to simplify its exploitation.

5 OZNAČBE
5 SYMBOLS

površina	A	m^2	area
specifična toplota	c_p	J/kgK	specific heat capacity
količnik toplotnega toka	C_R	-	heat flux factor
masni tok zunanjega zraka	g_o	-	outside air mass ratio
količnik kota	G	-	angle factor
specifična entalpija	h	J/kg	specific enthalpy
masni tok infiltracije	m_I	kg/s	infiltration mass flow rate
električna moč kompresorja	P_{KP}	W	compressor electrical power
gostota toplotnega toka	q	W/m^2	heat flux density
prostorninski tok sistema	V_{AC}	m^3/s	system volume flow rate
prenosne funkcije	X, Y, Z	W/m^{2}K	conduction transfer functions
količnik toplotne prestopnosti	α	W/m^{2}K	heat transfer coefficient
hladilno število	ε_H	-	COP - coefficient of preformance
toplotni tok	Φ	W	heat flux
količnik pretvorbe električne energije kompresorja	η_a	-	conversion factor to electrical power of compressor
temperatura	ϑ	^{o}C	temperature
gostota	ρ	kg/m^3	density

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6 REFERENCES

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Model določitve kritične hitrosti ventilacije v primeru požara v cestnem predoru pri izotermnih pogojih

A Critical-Velocity Determination of Road-Tunnel Ventilation in Isothermal Conditions of a Fire-Incident Model Test

Petar Donjerković - Miodrag Drakulić

Ta prispevek predstavlja eksperimentalno določitev kritične hitrosti zraka in značilnosti za oceno učinkovitosti vzdolžne ventilacije v cestnih predorih v primeru požara. Določitev kritične hitrosti zraka pri izotermnih razmerah vzdolžne ventilacije je potekala v cestnem predoru ″Sveti Rok″, ki so jo izvajali v Inštitutu za pomorske in posebne raziskave v Zagrebu. Posebna pozornost je bila namenjena analizam porazdelitve dima v neposredni bližini simuliranega ognja za različne požarne obremenitve in različne vzdolžne hitrosti zraka. Analiza je bila narejena s pomočjo vizualizacije porazdelitve ″mrzlega″ dima, ki je bil simuliran z mešanico hlapov helija in parafina. Prispevek ocenjuje eksperimentalne rezultate kritične hitrosti zraka na modelu ter rezultate nedavnih raziskav.

(Ključne besede: predori cestni, sistemi prezračevalni, kritična hitrost zraka, določevanje hitrosti)

This paper shows an experimental determination of the critical air velocity, characteristic for an evaluation of the efficiency of road-tunnel longitudinal ventilation in fire-incident conditions. Determination of the critical air velocity was made in isothermal conditions of a model testing of the "Sveti Rok" road-tunnel longitudinal ventilation, performed in the hydrodynamic laboratories of the Marine Research and Special Technologies Institute in Zagreb. Special attention was paid to the analysis of smoke distribution in the close vicinity of a simulated fire source for different fire loads and different longitudinal air velocities. The analysis was made by visualisation of the distribution of "cold" smoke simulated with the mixture of helium and paraffin vapours. The paper evaluates the results of an experimental determination of the critical air velocity on the scale-model with available recent results of ventilation-system field tests.

(Keywords: road tunnels, ventilation systems, critical velocity determination, air velocity)

0 UVOD

Ventilacijski sistemi imajo pomembno vlogo pri preprečevanju požarov v predorih zaradi odvajanja toplote in pri ″nadzoru″ dima. Zelo pomemben je ″nadzor″ dima pri vzdolžnih ventilacijskih sistemih, saj je pri tem tipu ventilacije dim, z uporabo impulznih ventilatorjev, nameščenih na stropu, odstranjen skozi isti prostor, kjer poteka evakuacija potnikov. Zaradi tega mora ventilacijski sistem v primeru požara zagotoviti dotok pare, ki mora potiskati dim v nasprotni smeri evakuacije potnikov in dostopa gasilcev. Kritična hitrost zraka je prav gotovo najbolj pomemben parameter za določitev učinkovitosti vzdolžne ventilacije v primeru požara. Označena je kot ″najmanjša vzdolžna hitrost pare, ki je povprečena prek prereza, pri kateri je dim ″odstranjen″. Glavna zahteva za uspešno odvajanje dima je doseči

0 INTRODUCTION

Ventilation systems have an important role in tunnel-fire protection because of their capability to withdraw the heat generated during the fire and to "control" smoke. Smoke control is extremely important in longitudinal tunnel ventilation systems since in this type of ventilation the smoke is forced, with the help of ceiling-hung impulse fans, through the same space of the tunnel tube through which the passengers' evacuation is carried out. Because of this, in the case of fire, the ventilation system must secure an efficient air stream which will push smoke in the direction opposite to the evacuation of passengers and firemen access. The critical air velocity is most certainly the essential parameter for determining the efficiency of longitudinal ventilation in fire conditions. It is defined as the "*minimum longitudinal air stream velocity, averaged along the cross-section, at which the smoke backlayering is made impossible*". Achieving the critical air velocity is a kritično hitrost zraka, ki omogoča intervencijo gasilcev ter njihovo varno delo v bitki z ognjem. Nezanesljivi ventilacijski sistemi, ki ne zagotovijo kritične hitrosti zraka v primeru požara, neposredno ogrožajo gasilce, ki so vstopili v predor in pričeli gasiti, pa tudi potnike, ki se umikajo prek nezadimljenega dela predora proti izhodu, drugemu predoru ali v zaklonišče.

basic prerequisite for successful tunnel smoke purging which enables the intervention on the part of fire brigades and their safe work on fire fighting. An unstable ventilation system, which cannot reach the critical air velocity in fire conditions, directly endangers firemen who have entered the tunnel tube and begun fire fighting, as well as the passengers who are moving, in the stage of evacuation, along the unsmoked part of the tunnel towards the exit, the other tunnel tube or the shelter.

1 TEORETIČNA DOLOČITEV KRITIČNE HITROSTI ZRAKA

1 THEORETICAL DETERMINATION OF CRITICAL AIR VELOCITY

Izrazi za oceno kritične hitrosti zraka v predoru (w_c) so razviti iz najbolj preprostih oblik, ki povezujejo odvisnost:

Expressions for estimating the critical air velocity in the tunnel (w_C) have evolved from the most simple form, which shows the functional connection:

$$w_C = f\left(\sqrt[3]{\frac{Q}{B_t}}\right) \quad (1),$$

kjer pomenita Q toplotno obremenitev in B_t širino predora. Thomasova empirična enačba:

where Q is the fire thermal load and B_t the tunnel tube width, through the Thomas' empirical expression:

$$w_C = \left[\frac{gQH}{\rho_0 T_0 c_p A}\right]^{1/3} \quad (2),$$

kjer so g gravitacijski pospešek, h višina predora, ρ_0 gostota zraka, T_0 temperatura vstopajočega zraka, c_p specifična toplota zraka, A površina prečnega prereza predora, kar vse vodi k spremembi Thomasovega izraza [1]:

where g is gravity, H is the tunnel tube height, ρ_0 is the air density, T_0 is the temperature of the incoming air, c_p the specific air heat and A the surface of the tunnel tube cross-section, all up to the modification of Thomas' expression which has been confirmed by field tests [1]:

$$w_C = K_1 K_2 \left(\frac{gQH}{\rho_0 T_D c_p A}\right)^{1/3} \quad (3),$$

kjer so:
- količnik $K_1 = Fr_C^{-1/3}$
- količnik $K_2 = 1 + 0{,}037\,(\text{strmina})^{0,8}$
- povprečna temperatura dima $T_D = \dfrac{Q}{\rho_0 c_p A w_C} + T_0$

where:
- coefficient $K_1 = Fr_C^{-1/3}$
- coefficient $K_2 = 1 + 0{,}037\,(\text{gradient})^{0,8}$
- average temperature of smoke $T_D = \dfrac{Q}{\rho_0 c_p A w_C} + T_0$

Enačba (3) za oceno kritične hitrosti (w_c) zahteva iterativni postopek, ki ga uporabljamo tudi pri računanju povprečne temperature dima. Froudovo število v količniku K še dodatno pripomore k zapletu ocene, saj ne poznamo vseh elementov za njegovo določitev.

The above-mentioned formula (3) for the critical velocity (w_C) estimate requires an iterative procedure since the same is also contained in the expression for the average smoke temperature. Introduction of the Froude number through the coefficient K_1 additionally complicates the estimate since not all elements for its determination are known.

2 DOLOČITEV KRITIČNE HITROSTI ZRAKA S PRESKUSI

2 EXPERIMENTAL DETERMINATION OF CRITICAL AIR VELOCITY

2.1 Splošno

2.1 General

Določitev kritične hitrosti zraka s preskusi:
a) testiranje ventilacije in možnosti požara,
b) na testnem modelu ventilacije in požara pri izotermnih in neizotermnih pogojih.

Najbolj obsežne terenske raziskave obnašanja različnih ventilacijskih sistemov v primeru požara so bile opravljene v zapuščenem

Experimental determination of critical air velocity can be made by:
a) field tests of ventilation and fire incident;
b) scale-model tests of ventilation and fire incident in isothermal and non-isothermal conditions.

So far the most complex and comprehensive field test of the behaviour of various ventilation systems in fire-incident conditions was performed in the abandoned Mepredoru Memorial [1] (ZDA, 1993 do 1995) pod pokroviteljstvom Federalne cestne administracije, skladno s programom Tehničnega komiteja 5.9 ASHREA. V sklopu omenjenih raziskav so bile poleg kritične hitrosti vzdolžnega sistema ventilacije raziskane tudi toplotne obremenitve do 100 MW. Rezultate ocen kritične hitrosti dobimo s spremenjeno Thomasovo enačbo. Raziskave so pokazale, da kritična hitrost zraka ne presega vrednosti 3 m/s v razponu toplotnih obremenitev od 5 do 100 MW.

Testni model pri neizotermnih pogojih temelji na toplotnih virih z bistveno zmanjšano toplotno obremenitvijo. Oka in Atkinson sta leta 1996 izvedla preskus neizotermnega testnega modela, ki je ugotavljal porazdelitev dima v povezavi z vzdolžno ventilacijo [2]. Glavni namen je bil določitev kritične hitrosti zraka v odvisnosti od različnih toplotnih obremenitev požara, ki je bil simuliran z zgorevanjem propana.

Testni modeli požara in ventilacije pri izotermičnih pogojih navadno temeljijo na t.i.″mrzlem″ dimu, ki je pravzaprav mešanica enega od lahkih plinov (npr. helij) z zrakom, dušikom ali ogljikovim dioksidom. Za namen boljše vizualizacije so dodali barvne komponente, npr. paro glicerina. Toplotne obremenitve v testnem modelu ne ustrezajo tistim v primeru požara, z njimi niti ne moremo predstaviti vseh potrebnih fizikalnih lastnosti požara kot celotnega pojava. Kakorkoli že, navkljub očitnim omejitvam, ki spremljajo raziskave ventilacije v primeru požara pri izotermnih pogojih, dobljene vrednosti resničnih meritev v primerjavi z računalniškimi simuliranji ne odstopajo veliko. Omenjeni rezultati se nanašajo na določitev kritične hitrosti zraka in vizualizacije porazdelitve dima v bližini simuliranega vira ognja.

2.2 Model določitve kritične hitrosti pri izotermnih pogojih

2.2.1 Model, namen in pogoji testiranja

Določitev kritične hitrosti zraka pri izotermnih pogojih so izvajali skupaj z modelom testiranja ventilacije v predoru Sveti Rok in v Inštitutu za pomorske in posebne raziskave v Zagrebu [3]. Model je vključeval uporabo vzdolžne ventilacije v razmeroma dolgem predoru z dvosmernim prometom. Namen testiranja je bil, poleg določitve vpliva prometa na učinkovitost delovanja ventilacijskega sistema, tudi napoved obnašanja sistema v primeru požara. Kritična hitrost zraka je bila določena za tri toplotne obremenitve 5, 10 in 20 MW. Podatki in rezultati so prikazani v preglednici 1.

morial tunnel [1] (USA, 1993 to 1995.), under the auspices of the Federal Highway Administration, according to the Technical committee 5.9 ASHREA program. The critical velocity of the longitudinal ventilation system, including the fire loads up to 100 MW was also determined within the scope of these tests. The tests resulted in a modification of the standard Thomas' formula for the critical velocity estimate which thus acquires the form of the above-mentioned expression (3). Subject tests have established that the critical air velocity does not exceed the value of 3 m/s for a wide range of fire loads from 5 to 100 MW.

Model tests in non-isothermal conditions are based on the real heat source with an essentially reduced heat load that is appropriate to the model. An example of a non-isothermal model test is testing of the smoke distribution in conjunction with the longitudinal ventilation made by Oka and Atkinson in 1996 [2]. The basic purpose of this testing was a determination of the critical air velocity depending on different heat loads of fire stimulated by the propane burner operation.

Model tests of the fire incident and tunnel ventilation in isothermal conditions are usually based on so-called "cold" smoke which is actually a mixture of one of the "light" gases (e.g. helium) with air, nitrogen or carbon dioxide. For the purpose of improved visualisation, coloured components are added, for example, glycerine vapours. This type of testing cannot model the heat loads adequately in case of fire, nor is it possible to present all the necessary physical properties of fire as a complex phenomena. However, in spite of obvious limitations which accompany the isothermal tests of ventilation in fire conditions, the obtained results of some physical values which characterise the behaviour of the ventilation system in fire conditions, have shown good correlation with field tests and computer simulations. First of all, the mentioned results refer to a determination of the critical air velocity and a visualisation of the smoke distribution close to the simulated fire source.

2.2 Determination of critical velocity in isothermal conditions of model tests

2.2.1 Model, purpose and conditions of testing

Determination of the critical air velocity in isothermal conditions was carried out during model testing of the ventilation of the *Sveti Rok* tunnel in the hydrodynamic laboratories of the Marine Research and Special Technologies Institute in Zagreb [3]. The proposed design solution included the use of longitudinal ventilation in a relatively long single-tube tunnel with bi-directional traffic. Determination of the critical velocity was made for three standard fire loads of 5, 10 and 20 MW. Because of the complexity of the mentioned tests the interval of fire loads was not extended to values above 20 MW. Input data and the results of the subject tests are shown in *Table 1.*

Zgoraj omenjene raziskave so se odvijale na tako imenovanih majhnih fizikalnih modelih (razmerje 1:25). Model predora je imel obračališče, dve zavetišči (oziroma vhoda v zavetišči), tri obcestna počivališča in pet baterijskih ventilatorjev z resnično dolžino 675 m (dolžina na modelu 27 m). Pleksi steklo (debeline 3 mm) je bilo nameščeno po predoru in omogočalo nadzor širjenja dima med simuliranjem požara in tudi nadzor pretoka prometa.

The above-mentioned model tests were carried out on a so-called “small” physical model (Scale 1:25) and for tunnel modelling the central section which includes one turning gallery, two shelters (i.e. entrances into shelters), three lay-bys for stopping vehicles and five fan batteries with the actual length of 675 m (model length 27 m). Perspex (3 mm in thickness) was used for the tunnel lining to enable monitoring of the spreading of smoke during the fire incident simulation as well as the control of traffic flow.

Preglednica 1. *Podatki in rezultati za določitev kritične hitrosti na modelu in v predoru*
Table 1. *Input data and results of critical velocity determination on model and on site*

NA TERENU ON SITE	***Toplotna obremenitev Thermal load***	***MW***	***5***	***10***	***20***
	ekvivalentna površina gorenja equivalent burning area	*m^2*	*2*	*4*	*8*
	nastala količina dima generated volume of smoke	*m^3/s*	*20*	*33*	*60*
NA MODELU ON MODEL	*ekvivalentna površina gorenja equivalent burning area*	*cm^2*	*32*	*64*	*128*
	nastala količina "mrzlega dima" generated volume of "cold smoke"	*l/s*	*6,4*	*10.6*	*19.2*
	pretok zraka skozi predor air flow through tunnel	*m^3/s*	*0,0393*	*0.0458*	*0.0467*
	hitrost toka zraka skozi model predora air stream velocity through the model tunnel tube	*m/s*	*0,423*	*0.493*	*0.503*
	razdalja med "čelom" dima in mestom gorenja distance of the smoke layer face from the place of fire	*m*	*-2,0 do/to -1,8*	*-2.0 do/to -1.8*	*-2.0 do/to -1.8*
REZULTATI RESULTS	***razdalja[1] med "čelom" dima in mestom gorenja (na kraju samem) distance[1] of the smoke layer face from the place of fire (on site)***	*m*	***- 50 do/to - 45***	***- 50 do/to - 45***	***- 50 do/to - 45***
	hitrost toka zraka skozi predor (na kraju samem) – kritična hitrost w_C air stream velocity through the tunnel (on site) - critical velocity w_C	*m/s*	***2,115***	***2,465***	***2,515***

(1) Negativen predznak pomeni, da je razdalja merjena v nasprotni smeri od smeri toka zraka med odstranjevanjem dima
(1) Negative sign denotes that the distance is measured in the direction contrary to the direction of air flow during the “smoke purging” regime

2.2.2 Rezultati

V skladu z rezultati testnega modela je odvisnost kritične hitrosti od toplotne obremenitve prikazana na sliki 1. Razvidno je, da krivulja kritične hitrosti enakomerno narašča glede na toplotno obremenitev in pri veliki toplotni obremenitvi se asimptotično približuje vrednosti 3 m/s, z drugimi besedami, občutljivost kritične hitrosti se zmanjšuje v območju večjih toplotnih obremenitev, kar v praksi omogoča uspešno odstranjevanje dima iz predora v širokem razponu toplotnih obremenitev do 100 MW s hitrostjo okrog 3 m/s.

Slika 2 prikazuje medsebojno odvisnost kritične hitrosti zraka in toplotne obremenitve s Froudovim številom kot parametrom. Prej omenjeni spremenjeni Thomasov izraz (3), ki je bil preverjen v predoru Memorial, je bil uporabljen tudi za določitev družine krivulj $w_c = f(Fr,Q)$. Razvidno je, da je krivulja $w_c = f(Q)$, ki smo jo dobili s ekstrapolacijo merjenih vrednosti testnega modela, ki so bili izvajani v

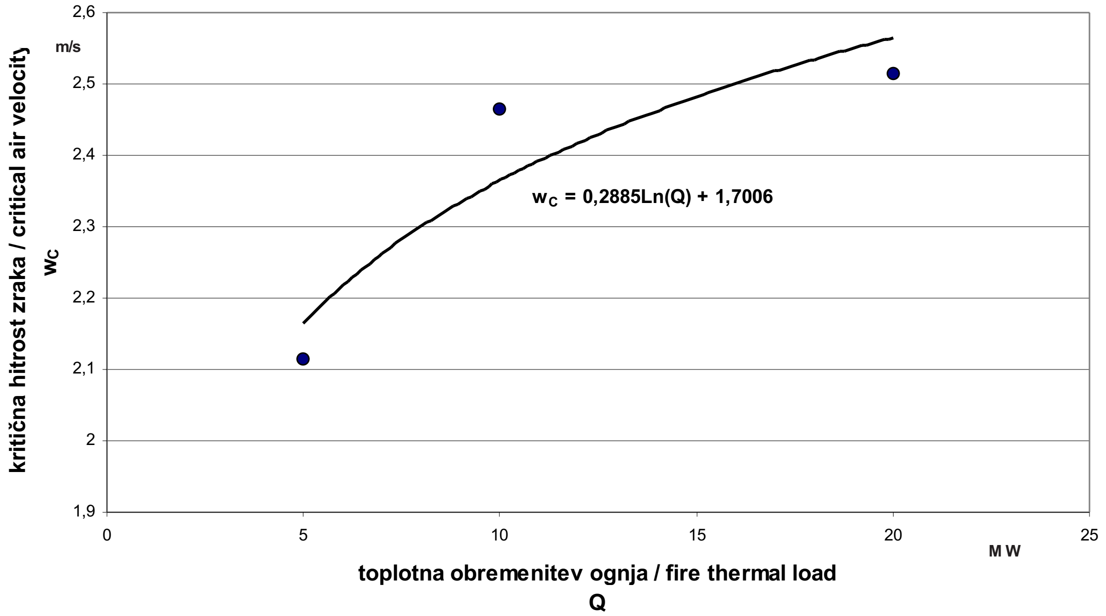
2.2.2 Results

In compliance with the results of model tests, the critical velocity dependence on the fire load is shown in *Figure 1*. It is clear that the critical velocity is a uniformly growing fire load curve which for high fire loads asymptotically aims at the value of 3 m/s. In other words, the “sensitivity” of the critical velocity drops in the area of high fire loads and in practice it enables the successful smoke purging of the tunnel for a wide range of fire loads up to about 100 MW with the speed of about 3 m/s.

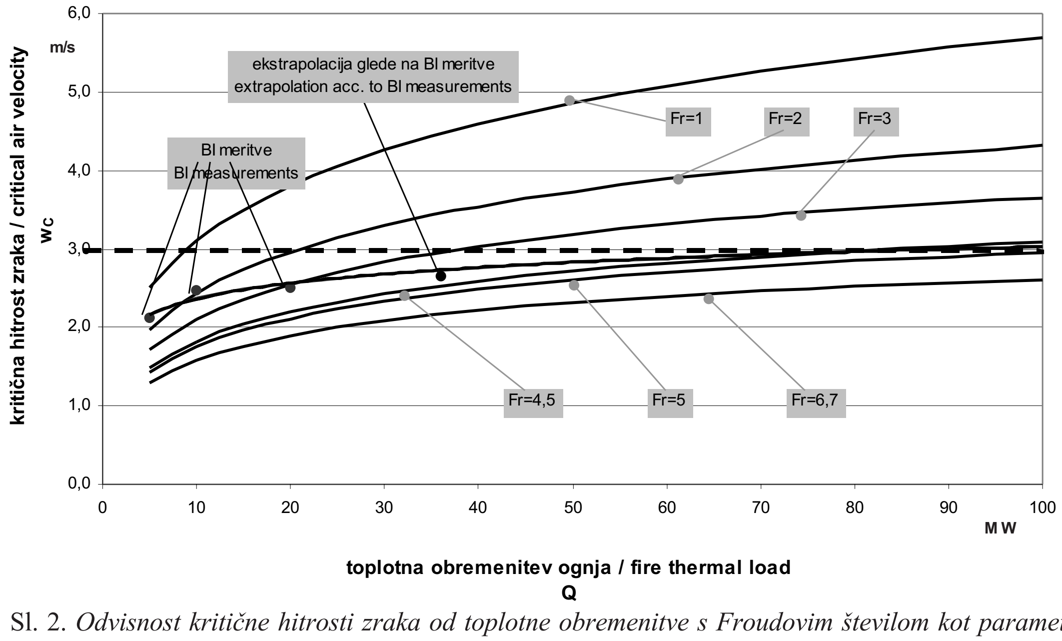
Figure 2 shows the interdependence of the critical air velocity and the fire thermal load with the Froude number as a parameter. For this, previously mentioned modified Thomas’ expression (3), checked during testing in the Memorial tunnel was used for determining the curve family $w_C = f\,(Fr, Q)$. It is visible that the curve $w_C = f\,(Q)$, obtained by extrapolation of measured values of model tests carried out in the Marine Research and Special Technologies Insti-

Iinštitutu za pomorske in posebne raziskave (BI), se dobro ujemajo s teoretično krivuljo za vrednost parametra Froudovega števila 4,5, še posebno v območju višjih toplotnih obremenitev. Enako vrednost Froudovega števila so omenili tudi avtorji testiranj v predoru Memorial [1] kot vrednost, ki najbolj približa teoretične in praktične preskuse. Določene odmike od kritičnih hitrosti, merjenih v BI, v primerjavi s teoretičnimi vrednostmi v območju toplotnih obremenitev, lahko pojasnimo z dejstvom, da je bila gostota mrzlega dima nespremenljiva za celotno področje med 5 in 20 MW, kar pa ni stvarno. Omenjena gostota ustreza

tute (BI), matches well the theoretical curve for parameter value of Froude number 4.5, particularly in the area of higher fire loads. The same value of Froude number is mentioned by the authors of tests performed in the *Memorial tunnel* [1], as the value which best “adapts” the theoretical expression to the field tests. Certain deviations from critical velocities measured in the BI, in comparison with theoretically computed value in the range of lower fire loads, are explained by the fact that the density of “cold” smoke was kept constant for the entire testing interval from 5 to 20 MW, which is not a physical reality. The mentioned density corresponded to an assumed smoke



Sl. 1. *Odvisnost kritične hitrosti zraka od toplotne obremenitve ognja*
Fig. 1. *Dependence of critical air velocity upon simulated fire load*



Sl. 2. *Odvisnost kritične hitrosti zraka od toplotne obremenitve s Froudovim številom kot parametrom*
Fig. 2. *Dependence of critical air velocity upon simulated fire load, with Froude number as parameter*

načrtovani temperaturi dima 1350 °C, kar je še vedno prevelika vrednost za požare take toplotne obremenitve. Upoštevajoč dejstvo, da je dejanska temperatura dima za omenjene temperaturne obremenitve manj od 1350 °C in bi zato morala biti gostota mrzlega dima večja od tiste, ki so jo uporabili pri testiranjih (0,182 kg/m^3). Iz tega lahko sklepamo, da bi krivulja BI in teoretična krivulja za w_c dale boljše rezultate, kakor če bi računali z manjšimi toplotnimi obremenitvami.

temperature of 1350°C, which is still too high a value for fires of this low thermal load. Considering the fact that the actual temperature of smoke for the mentioned fire loads is less than 1350°C and that therefore the density of "cold" smoke should have been higher than the one used during model testing (0.182 kg/m^3), it can be concluded that the BI curve and the theoretical curve for w_C would have given much better agreement than the achieved one at mentioned lower fire loads.

3 SKLEP

Vrednosti kritične hitrosti zraka, ki smo jih dobili s testiranjem ventilacije v predoru Sveti Rok pri izotermnih pogojih, se ujemajo s teoretičnimi izračuni. Majhne odmike v območjih manjših toplotnih obremenitev lahko pojasnimo s povečanjem gostote mrzlega dima, ki ustreza dejansko nižjim temperaturam dima v predorih. Gostota uporabljenega mrzlega dima, ki ustreza resnični temperaturi dima 1350 °C je nižja od tiste, ki se pojavi v predorih v primeru manjših toplotnih obremenitev. Izotermni pogoji testiranja niso vplivali na verodostojnost pridobljenih podatkov o kritični hitrosti zraka, čeprav je problem fizikalnih vrednosti povezan izključno z delovanjem ventilacijskega sistema pri neizotermnih pogojih.

3 CONCLUSION

Measured values of critical air velocities obtained by model tests of the Sveti Rok tunnel ventilation in isothermal conditions have a high degree of agreement with theoretically computed and on-site confirmed values. The slight deviations noted in the area of lower fire loads can be annulled by an increase of the "cold" smoke density that is appropriate to actually lower temperatures of smoke on site. In that sense the density of used "cold" smoke, which corresponds to the real temperature of smoke of 1350°C, has shown to be lower than the one which occurs on site for the case of observed smaller values of fire loads. Isothermal conditions of testing, however, have not affected the credibility of the obtained data on the necessary critical air velocities, although it is the question of the physical value which is connected exclusively with operation of the ventilation system in fire, i.e. in distinctly non-isothermal conditions.

4 OZNAČBE
4 SYMBOLS

kritična hitrost	w_C	m/s	critical velocity
toplotna obremenitev ognja	Q	W	fire load
širina predora	B_t	m	width of tunnel
višina tunela	H	m	height of tunnel tube
gostota zraka	ρ_0	kg/m^3	air density
temperatura zraka	T_0	K	air temperature
temperatura dima	T_D	K	smoke temperature
spec. toplota zraka	c_p	J/kgK	spec. air heat
površina prereza predora	A	m^2	tunnel cross-section area
Froudovo število	Fr	-	Froude number

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5 REFERENCES

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Ponazoritev enofaznega toka v križnih ploščnih prenosnikih toplote

Visualtization of One-Phase Flow in Chevron-Plate Heat Exchangers and Their Performance

Damir Dović - Björn Palm - Srećko Švaić

Dandanes so razširjeni različni tipi lamelnih menjalnikov toplote v enojnem in dvofaznem tokovnem režimu s križnimi valovnimi vzorci znotraj številnih vrst uporab zaradi njihove zgoščenosti in sposobnejše toplotno-hidravlične storitve, ko jih primerjamo z drugimi tipi menjalnikov toplote.

Pred kratkim so bile opravljene številne eksperimentalne študije, ki so dostopne v literaturi, da bi spoznali vpliv kotov grbin in globine grbin proti valovnemu razmerju dolžin (b/l) na tokovni vzorec in spremembi prenosa toplote ter padca tlaka.

Zato, da bi razjasnili zapletenost predmeta raziskave, so bili izvedeni vizualni testi na modelu PPT (ploščnem prenosniku toplote) z enojnim kanalom, ki je sestavljen iz kovinske in plastične prosojne lamele z identičnimi grebeni.

(Ključne besede: prenosniki toplote, prenosniki lamelni, vizualizacija tokov, meritve karakteristik)

Modern plate heat exchangers with chevron corrugation patterns are spread across a range of applications both in one- and two-phase flow regimes due to their compactness and superior thermal-hydraulic performance when compared to the other types of heat exchangers.

Recently a limited number of experimental studies have been undertaken to understand the influence of corrugation angles and the ratio of corrugation depth to wave length (b/l) on the flow pattern and in turn on the heat transfer and pressure drop.

In order to clarify this complex issue, visualization tests have been performed on a model of a plate heat exchanger (PHE) having only a single channel composed of one metal and one plastic transparent plate with identical corrugation.

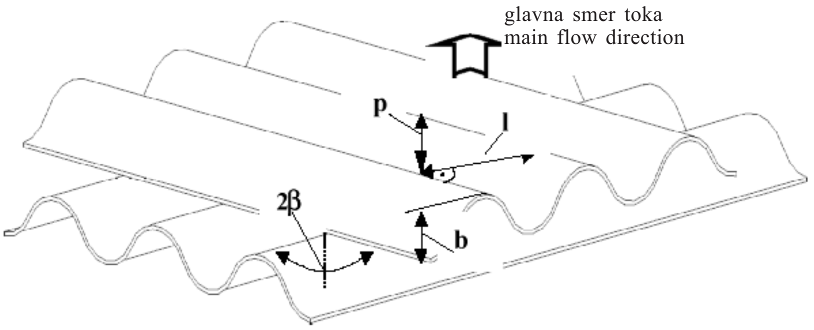
(Keywords: heat exchangers, plate heat exchangers, flow visualizations, measurement characteristics)

0 UVOD

Uporabljena osnovna geometrijska oblika pri vseh tipih PPT vsebuje številne ozke kanale, ki so sestavljeni iz dveh valovitih lamel (glavna razdalja je manjša od 3 mm) s poševnimi rebri pod kotom β v smeri glavnega toka in potujejo v nasprotni smeri na sosednje lamele (sl. 1). Takšna ureditev tvori zapleten tridimenzionalni tokovni vzorec in s tem tok prehaja iz laminarnega v turbulentni že pri Re = 10. Popolni turbulentni tok se doseže pri vrednosti Re = 400 do 800, odvisno od kota β, ki je najvplivnejši parameter. Medsebojno delovanje podtokov, ki sledijo vzdolž medrebernih utorov, spremljajo nastajanje drugotnih vrtinčastih tokov, kar ima za posledico visok koeficient prenosa toplote s spremenljivim tlačnim padcem (α=1000 W/m^{2}K, $\Delta p/L$ = 27.000 Pa za Re = 4000 in β = 60°).

0 INTRODUCTION

The basic geometry used in all types of PHEs consists of a number of narrow channels each composed of two corrugated plates (mean distance less than 3 mm) with chevrons inclined at an angle β to the main flow direction and running in opposite directions on adjacent plates (Fig1). Such an arrangement produces a complex 3D flow pattern with the transition from laminar to turbulent flow begining at Re= 0. Fully turbulent flow is achieved at Re=400 to 800 depending upon the angle β, which is the most influencial parameter. Interactions between substreams flowing along the chevron furrows accompanied by the generation of secondary swirl flows are responsible for high heat-transfer coefficients with acceptable pressure drops ((i.e. α= 10000 W/m^2 K, $\Delta p/L$= 27.000 Pa for Re=4000 and β=60°).



Sl. 1 *Tridimenzionalni kanal*
Fig.1. *3D channel*

Izvedeni sta bili dve seriji meritev za lameli s kotom 28° in 61°, ki se uporabljajo v tesnjenih in varjenih ploščnih prenosnikih toplote. Barvilo je bilo vneseno v kanal z uporabo votle cevke pri določenih točkah znotraj prosojne lamelne površine pa tudi v mesto vstopa. V primernih časovnih korakih je digitalna kamera posnela tokovni vzorec. Testni tekočini sta bili voda in voden glikol. Različne tokovne razmere so bili znotraj delovnega območja: Re = 0,1 do 600. Spodaj so prikazani nekateri najbolj zastopani rezultati.

Two sets of measurements have been carried out for plates with angles 28° and 61°, normally used in gasketed and brazed PHEs, respectively. Dye was introduced into the channel by using a hypodermic needle at certain points within the transparent plate surface as well as into the inlet port. A digital camera recorded the flow pattern at appropriate time intervals. The test fluids were water and aqueous glycol. Flow conditions were varied within the range Re=0.1 to 600. Some of the most representative results are shown below.

1 HOLGER MARTIN-OVA KORELACIJA

Obsežen literarni pregled priča o maloštevilnih objavljenih korelacijah glede prenosa toplote in padca tlaka v ploščnih prenosnikih toplote (PPT) in so še vedno skrivnost proizvajalcev. Zaradi omenjenega je treba popularizirati korelacije, katerih namen je oskrbeti uporabnike z zanesljivimi podatki o lamelah s poljubno geometrijsko obliko. To delo omogoča primerjavo med objavljenimi eksperimentalnimi rezultati za prenos toplote in tlačnega padca z rezultati, dobljenih po H. Martin-ovi (7) polempirični korelaciji (enačba 2), ki temelji na Lévêque-ovi rešitvi (enačba 1) za pogoje termičnega razvijanja. Prav tako temelji na objavljenih rezultatih vpliv pojava razmerja *b/l* (ali *b/p*) na lamele, pri katerih je termično-hidravlična storitev izmerljiva. Zaradi različnih definicij dimenzioniranih skupin (Nu, Re, f) in tudi prenosa toplote in križnega toka na prečni površini so bili pri različnih avtorjih v prejšnjih objavljenih rezultatih preračunani za možno primerjavo:

1 HOLGER MARTIN'S CORRELATION

A comprehensive literature survey proved that there are only a few correlations published for heat transfer and pressure drop in PHEs as they are still the proprietary information of manufactures. There is a need for a generalized correlation that would provide users with reliable data for plates with arbitrary geometry. This work provides a comparison between published experimental results for heat transfer ($Nu/Pr^{1/3}$) and pressure drop (f) with results obtained from H. Martin´s [7] semi-empirical correlation (Eq.2) based on the Lévêque solution (Eq.1) for a thermally developing condition. Also based on published results, the influence of aspect ratio (*b/l* or *b/p*) on the plate thermal-hydraulic performance is quantified. Due to the different definitions of dimensionless groups (Nu, Re, f) as well as heat transfer and flow cross-sectional area by different authors, previously published results were recalculated to enable a comparison:

$$Nu_{m,T} = 0,40377\left(f_D \,\mathrm{Re}^2 \,\mathrm{Pr}\; d_h / x\right)^{1/3} \text{-Lévêque} \tag{1}$$

$$Nu = 0,122\left(f_{D,H.M.} \,\mathrm{Re}^2 \,\mathrm{Pr}\; \sin(2\beta)\right)^{0.374} \text{-Martin} \tag{2}$$

$$d_h / x = \frac{d_h}{p}\sin(2\beta) \tag{3}$$

$$\frac{1}{\sqrt{f_{D,H.M.}}} = \frac{\cos\beta}{\sqrt{b\tan\beta + c\sin\beta + f_{D\sin e}/\cos\beta}} + \frac{1-\cos\beta}{\sqrt{af_{corr.}}} \tag{4}$$

b = f (tokovni obrat na robovih lamele in linije centra)
c = f (križanje)

b = f (flow reversals at plate edges and central line)
c = f (crossings)

2 REZULTATI

2 RESULTS

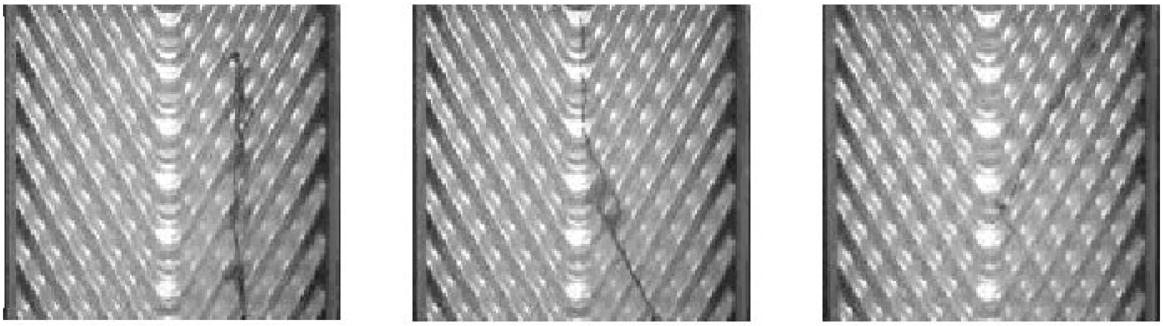
Lamela 28°

Plate 28°

a) barvilo, vbrizgano blizu prosojnega zidu, navzkrižni tok, povečanje utorne komponente z Re

a) dye injected close to the transparent wall, criss-cross flow, increase of the furrow component with Re

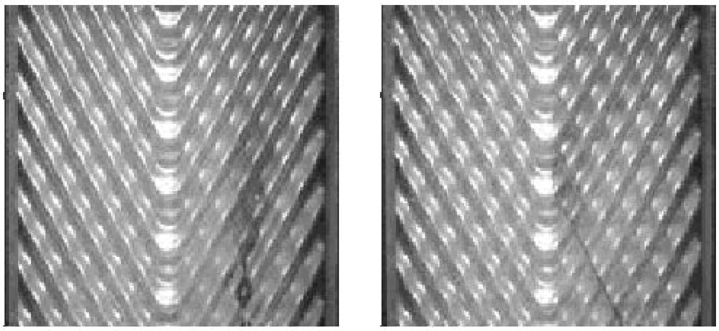
Re = 0,1 Re = 10 Re = 250



b) barvilo, vbrizgano v srednji del križnega toka prečne površine (osnovna celica), prebrana vzdolžna komponenta in prevlada utorov pri večjem Re

b) dye injected in the middle part of flow cross-section area (basic cell), evidence of presence of longitudinal component and dominance of the furrow one for higher Re

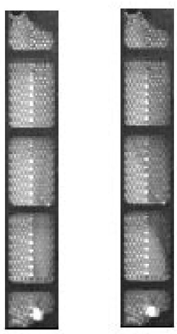
Re = 10 Re = 250



c) barvilo, vbrizganov spodnji del desne strani kanala, popolno pomanjkanje mešanja med dvema lamelnima polovicama pri manjšem Re

c) dye injected in the lower part on the right-hand side of the plate, total absence of mixing between two halves of plate for lower Re

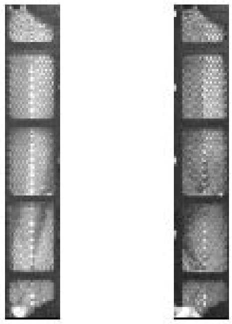
Re = 6 Re = 85



d) barvilo, vbrizgano v spodnji del leve strani (vnosno mesto). Večje hitrosti na tem delu lamele povzroča mešanje med dvojnimi polovicami, slaba razporeditev med dvema polovicama pri večjem Re

d) dye injected in the lower part of the left-hand side Higher velocities at this part of the plate cause mixing between the two halves, less pronounced maldistribution between two halves at higher Re

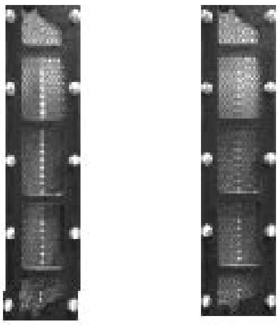
Re= 13 Re = 140



e) barvilo, vbrizgano v vstopno mesto, slaba razporeditev pri manjšem Re (višja hitrost na levi strani lamele)

e) dye injected in the inlet port, maldistribution at low Re (higher velocity at the left-hand side of the plate)

Re = 30 Re = 500



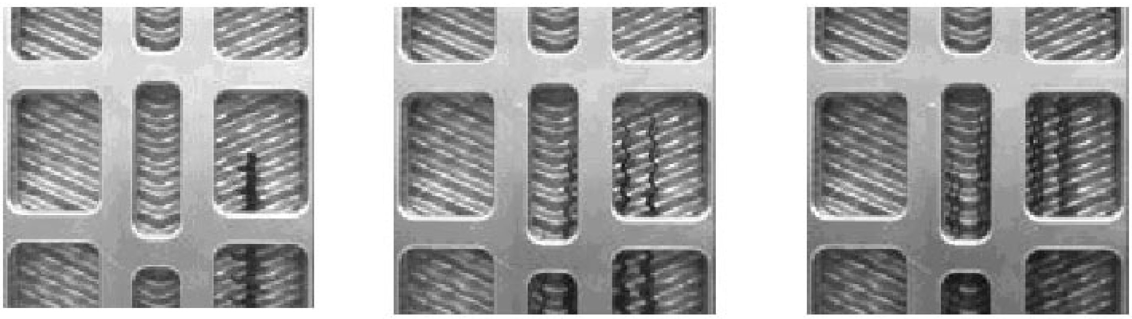
Lamela 61°

Plate 61°

a) barvilo, vbrizgano na poljubnih mestih znotraj križnega toka prečne površine, valujoč vzdolžni tok, utorni tok se poveča z Re in močnejše mešanje dveh podtokov znotraj celice pri večjem Re

a) dye injected at arbitrary points within flow cross-section area, wavy longitudinal flow, increase of furrow flow with Re and more thorough mixing of the two substreams within the cell at higher Re

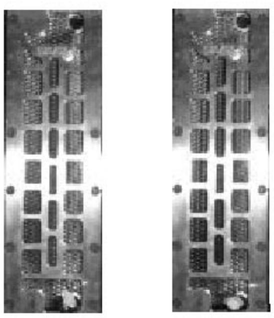
Re = 0,5 Re = 10 Re = 60



b) bolj izenačena porazdeljenost hitrosti, ni razlike med dvema polovicama

b) more even velocity distribution, no difference between the two halves

Re = 10 Re = 80



3 SKLEP

Predstavljeni rezultati prikazujejo navzočnost dveh tokovnih komponent, ki se pojavita hkrati v obeh testnih kanalih. Vzdolžna komponenta je prevladujoča pri lameli s kotom 61° in povzroča tako imenovan valovni vzdolžni tokovni vzorec. V tem primeru glavni del vsakega podtoka spremeni smer znotraj sosednjih celic sledeč krivuljni obliki stene od ene lamele do sosednje, medtem ko manjši del napreduje v svoji smeri in je izpostavljen mešanju z nasprotnim podtokom. Tok v 28° kanalu se imenuje navzkrižni tok, ki je v glavnem določljiv z utorno komponento, s tem glavni del vsakega podtoka sledi utorom in spremeni smer na robovih ter na sredini lamele. Manjši del podtoka, ki zavzame centralni del kanala (celice), spremeni smer na površini prečnega odseka v vsaki celici (vzdolžna komponenta) ter izmenično sledi po robovih glavnih delov obeh podtokov. Mešanje dveh podtokov je manj popolno in je učinkovita dolžina toka krajša, kar pojasnjujeta manjši koeficient prenosa toplote in faktor trenja za lamele z majhnim kotom β.

Povečanje Re števila in *b/l* vodi do večjega vpliva utorne komponente na vzorčni tok. Upoštevajoč lamele s prevladujočo vzdolžno komponento (večji koti) se zdi prikladno za prenos toplote, odkar se oba glavna podtoka popolnoma mešata znotraj celice. Nizek *b/l* bo povečal vpliv vzdolžne komponente, ki je zaželen pri lamelah z majhnimi koti, kar pomeni boljše mešanje med obema utorno prevladujočima podtokoma (velika stična površina med sekajočimi podtokovi). Na drugi strani zaradi manjšega koeficienta prenosa toplote v glavnem toku skozi sinusni kanal (utor) nasprotuje temu učinku. Zato je treba odkriti celice s takšnim *b/l*, ki dosegajo največje termične storitve kot funkcijo Re števila in kota.

Mešanje med tokovi, ki si sledijo ločeno, vzdolžno z dvema lamelnima polovicama, je slabotno, ko je kot 28° in zelo dobro v primeru kota 61°. Slaba razširjenost pri nizkem Re je med levim in desnim delom kanala merljiva pri lameli 28°.

Primerjava med H. Martin-ovo korelacijo in eksperimentalnimi rezultati petih avtorjev odkriva relativno dobro ujemanje v $Nu/Pr^{1/3}$ pri treh avtorjih – Heavner [5], Bond [6], Muley et.al. ([3] in [4]), pri katerih so rezultati znotraj ± 20 % in za Okado [2] (znotraj ± 25 %), medtem ko so večja razlikovanja v primerjavi s Focke [1] (do + 60 %). Računske krivulje za vsak nagibni kot se ujemajo z eksperimentalno doseženimi linijami v vseh tokovnih režimih. V vseh primerih so opazne večje razlike v primerjavi s faktorji trenja – do ± (40 do 60) %. To bi pomenilo, da bi se geometrično odvisni koeficienti a, b, c v H. Martin-ovi formuli morali prilagoditi vsaki posamezni geometrijski obliki, namesto

3 CONCLUSION

Visualization results showed the presence of two flow components occurring simultaneously in both tested channels. The longitudinal component is dominant for the plate with an angle 61° producing the so-called wavy longitudinal flow pattern. In this case the main part of each substream changes direction within adjacent cells following the sinusoidal shape of the walls from one plate to the adjacent one, while a minor part proceeds in the first direction (furrow component) being mixed with the opposite substream. The flow in the 28° channel is referred to as the criss-crossing one, being mainly determined by the furrow component where the main part of each substream follows furrows and changes direction at the edges and at the middle line of the plate. The minor part of the substreams that occupies the central part of the channel (cell) cross-section area changes direction in every cell (longitudinal component) flowing alternatively at the edges of the main parts of both substreams. Mixing between two substreams is, therefore, less thorough and the effective flow length shorter which explains lower heat transfer coefficients and friction factors for plates with a lower angle β.

An increase of Re number and *b/l* will lead to a greater influence of the furrow component on the flow pattern. Considering plates with a dominant longitudinal component (higher angles) this appears to be beneficial for the heat transfer since the two main substreams are mixed more thoroughly within the cell. Lower b/l will increase the influence of the longitudinal component which is desirable for plates with lower angles as it means better mixing between the two dominant furrow substreams (large contact area between crossing substreams). On the other hand, the consequent lower heat-transfer coefficient in the main flow through the sinusoidal duct (furrow) counteracts this effect. Hence, this requires discovering which *b/l* ratio would yield the best plate thermal performance as a function of the Re number and angle.

Mixing between streams flowing separately along two halves of the plate is weak when the angle is 28°, and very good for an angle 61°. At low Re, maldistribution between the left and right part of the channel is observed for the 28° plate.

Comparison between the correlation of H. Martin and the experimental results from five authors reveals relatively good agreement in $Nu/Pr^{1/3}$ for three authors – Heavner et al. [5], Bond [6], Muley et al. ([3], [4]) where the results are within ±20%, and for Okada et al. [2] (within ±25%) while large discrepancies are encountered in the comparison with Focke et al. [1] (up to +60%). Calculated curves for each inclination angle match well with the experimentally obtained lines in all flow regimes. Considerably higher deviations are present in a comparison of friction factors – up to ±(40 to 60)% in all cases. This would mean that the geometry-dependent coefficients a, b, c in the H. Martin formula should be adjusted for each particular geometry in question uporabljanja standardne serije parametrov, kakor je predlagal H. Martin. Rezultati Okade [2] prikazujejo povečanje toka prenosa toplote z lamel enakega kota *β* in projektnega območja (enaka prostornina kanala) pri enakem razmerju masnega toka (hitrost), ko je večje razmerje *b/p* (*b/l*), ampak se zmanjša z lamel zaradi večjega padca tlaka.

Nadaljnje meritve toplotnih in hidravličnih karakteristik v vidno raziskanih križnih kanalih, kakor tudi porazdelitev temperatur vzdolž vsakega kanala, bodo poskrbeli za več informacij glede lokalnih in povprečnih vrednosti za čisto laminarno in prehodno področje.

instead of using a standard set of parameters as originally proposed by H. Martin. Results from Okada et al. [2] showed an increase of heat flux transferred with plates having the same *β* and projected area (same channel volume) at the same mass flow rate(velocity) when the aspect ratio *b/p (b/l)* is higher but also a decrease of the plate "goodness" due to the higher pressure drop.

Ongoing measurements of thermal and hydraulic characteristics of the visually explored chevron channels as well as temperature distribution along each channel will provide more information concerning local and average values for the pure laminar and transient region.

4 OZNAČBE
4 SYMOBLS

konstante v H. Martin-ovi korelaciji	a, b, c		constants in the H. Martin correlation
globina gube (višina celice)	b	mm	corrugation depth (cell height)
hidravlični premer	$D_h = \frac{4\ x\ \text{prostornina/volume}}{\text{mokro obmoèje/wetted area}} = \frac{2b}{\phi}$	mm	hydraulic diameter
moč črpanja	$E_P = \frac{\dot{m}\ \Delta p}{\rho}$	W	pumping power
faktor trenja	$f = \frac{\Delta p}{4\left(\frac{L}{D_h}\right)\frac{\rho u^2}{2}}$		Fanning friction factor
Darcyjev faktor trenja	$f_D=4f$		Darcy friction factor
lamelna dolžina	L	m	plate length
dolžina vala gube	L	mm	corrugation wave length
masni tok	$\dot{m}$	kg/m²s	mass flux
Nusselt-ovo število	$\mathrm{Nu} = \frac{\alpha\ d_h}{\lambda}$		Nusselt number
vrh grbe (v smeri glavnega toka)	p	mm	corrugation pitch (in direction of main flow)
Prandtl-ovo število	Pr		Prandtl number
tlačni padec v	Δp	Pa	pressure drop
toplotni tok	Q	W	heat flux
Reynolds-ovo število	$\mathrm{Re} = \frac{\dot{m}\ d_h}{\mu}$		Reynolds number
povprečna hitrost	u	m/s	mean velocity
vzdolžna koordinata	x	m	axial (flow direction) coordinate
koeficient prenosa tolote, ki se nanaša na razvito površino	α	W/m²K	heat-transfer coefficient referred to the developed surface area
nagibni kot gube relativen na navpično smer	β	°	corrugation inclination angle relative to vertical direction
faktor povečanja (razmerje razvite/projecirana površina prenosa toplote)	ϕ		enhancement factor (ratio developed/ projected heat transfer surface area)
toplotna prevodnost	λ	W/mK	thermal conductivity
dinamična viskoznost	μ	Pa·s	dynamic viscosity
gostota	ρ	kg/m³	density

Indeksi		**Subscripts**
lamela s kotom $\beta = 90°$	corr.	plate with $\beta=90°$
Holger Martin	H.M.	Holger Martin
projecirana površina prenosa toplote	p	projected heat-transfer surface area
sinusnoidni kanal	sine	sinusoidal duct

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Razvoj uporabnih termografskih metod

The Development of Applied Thermographic Methods

Mladen Andrassy - Srečko Švaić - Ivanka Boras *

Termografija je nestična metoda za merjenje temperature in njene porazdelitve po površinah na predmetih. Temelji na infrardečem (IR) sevanju. Moderne termografske naprave podajajo časovno temperaturno porazdelitev, ki je poleg nestika glavna prednost metode. To daje termografiji zelo pomembno orodje, ki ga uporabljajo na vseh tehničnih področjih in tudi v medicini, biologiji itn.

Naslednji pregled daje osnove termografije in nekaj primerov kakovostne in kolikerostne termografije, ki pokriva velik spekter različnih uporab teh merskih tehnik na področju testiranja, razvoja izdelkov in znanstvenega raziskovanja.

(Ključne besede: termografija, razvoj metod, naprave termografske, uporaba termografije)

Thermography is a contactless method for the measurement of temperature and its distribution on the surfaces of objects. It is based upon the registration of infrared (IR) radiation from the object. Modern thermographic devices give the real-time surface temperature distribution, which combined with the absense of any contact is the basic advantage of the method. This makes thermography a very useful tool which has applications in all technical areas including medicine, biology etc.

The following review provides the basics of thermography and a couple of examples from qualitative and quantitative thermography indicating the wide spectrum of possible applications of this measuring technique in the field of surveillance, product development and scientific research.

(Keywords: termography, method developments, termographic equipment, termography applications)

0 UVOD

IR sevanje je znano skoraj 200 let in ga je odkril sir William Herschel (1738 do 1822) in ugotovil, med merjenjem toplotnih učinkov sončnega sevanja, da sevanje obstaja tudi nad rdečo svetlobo zunaj vidnega področja. IR je elektromagnetno sevanje v obsegu valovnih dolžin λ = 0,8 do 1000 μm, kar pomeni, da se širi v okolico vidne svetlobe (0,4 do 0,8 μm) (sl. 1). Kot preostala sevanja, je IR sevanje izpostavljeno osnovnim zakonom sevanja črnega telesa [1]:

1. Planckov zakon porazdelitve energije:

0 INTRODUCTION

IR radiation has been known for almost 200 years. Sir William Herschels' (1738 to 1822) measurements of thermal effects in the solar radiation spectrum revealed that light exists beyond red, outside the visible region. IR is an electromagnetic radiation in the range of wavelengths λ = 0.8 to 1000 μm, which means that it extends close to the range of visible light (0.4 to 0.8 μm), as shown in Fig. 1. Like all other radiation, IR is subject to the basic laws of black-body radiation [1]:

1. Planck's law of spectral energy distribution:

$$\mathrm{d}E_{\mathrm{c}} = \frac{\mathrm{c}_1}{\lambda^5 \exp(\mathrm{c}_2 / \lambda \mathrm{T}) - 1} \mathrm{d}\lambda \qquad (1)$$

glede na kar je del energije povezan z valovno dolžino *d*λ in je odvisen od same valovne dolžine in absolutne temperature *T*.

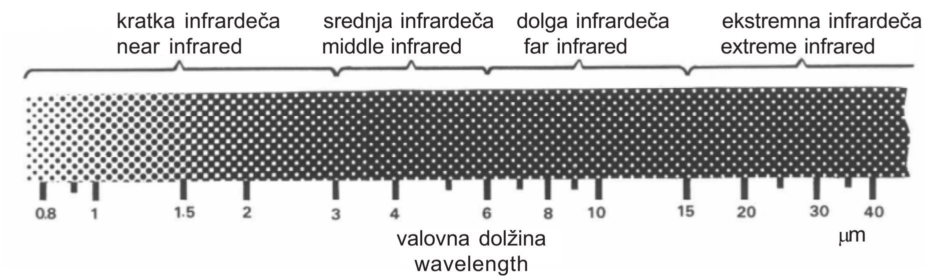
2. Wienov zakon

according to which the amount of energy radiated at a band of wavelengths dλ depends on the wavelength itself and the absolute temperature *T*.

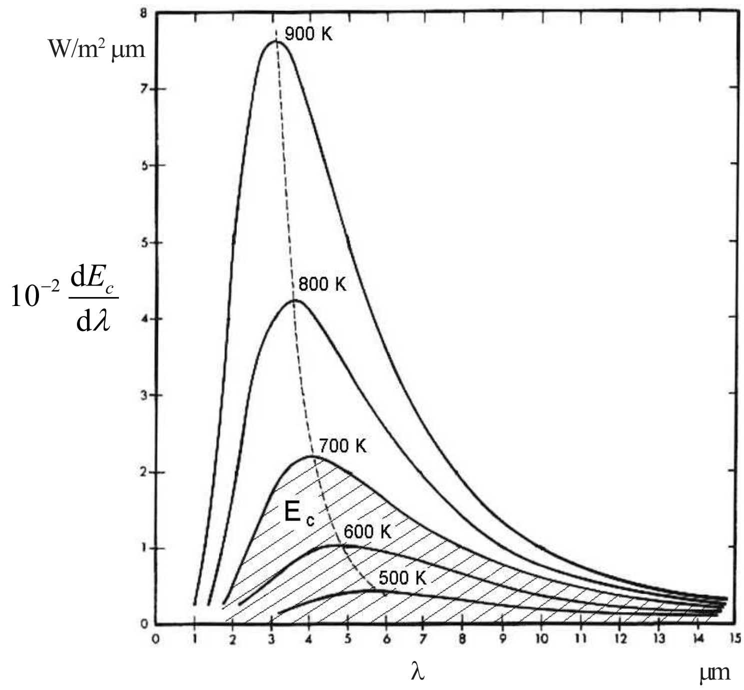
2. Wien's law:

$$\lambda_{\max} T = \mathrm{c}_3 \qquad (2)$$

* Termogrami / Thermograms by: Kruno Petrović



Sl. 1. *Elektromagnetni spekter*
Fig. 1. *The electromagnetic spectrum*



Sl. 2. *Porazdelitev spektralnega sevanja*
Fig. 2. *Distribution of spectral radiation*

pravi, da se največja valovna dolžina sevanja λ_{max} v Planckovi porazdelitvi premika v del z manjšimi valovnimi dolžinami pri naraščanju temperature.
3. Integracija Planckove enačbe (1) vodi do obrazca za celotno sevano energijo iz 1 m² površine s temperaturo *T*, ki sta jo empirično dobila Stefan in Boltzmann:

stating that the maximum radiation intensity wavelength λ_{max} in Planck's distribution shifts to the range of shorter waves with an increase in the temperature.
3. Integration of Planck's equation (1) yields the formula, obtained empirically by Stefan and Boltzmann, for the total energy radiated by 1 m² of a surface at the temperature *T*:

$$E_c = 5,67 \cdot 10^{-8}\, T^4 \qquad (3).$$

Slika 2 predstavlja omenjene zakone.

Za praktično uporabo postane zelo pomemben Kirchoffov zakon. Pravi, da telesa v toplotnem ravnovesju oddajajo ravno toliko svetlobe, kolikor jo absorbirajo, kar pomeni, da je sevalni koeficient ε enak absorpcijskemu koeficientu α. Sevalni koeficient je razmerje med oddano energijo površine in oddano energijo črnega telesa pri enaki temperaturi:

Fig. 2 represents the cited laws.

For practical applications of thermography, the Kirchoff rule becomes specially important. It states that bodies in thermal equilibrium emit as much energy as they absorb, which means that the emissivity coefficient ε of their surface equals the absorption coefficient *a*. The emissivity coefficient, on the other hand, is the ratio of the emitted energy of a surface to the emitted energy of a blackbody at the same temperature:

$$0 \le \varepsilon = E / E_c \le 1 \qquad (4).$$

Tako za črno telo velja $\varepsilon_c = \alpha_c = 1$, kar pomeni, da absorbira samo sevano energijo brez zrcaljenja ali prepustnosti. Po drugi strani telesa, ki nimajo lastnosti črnih teles, absorbirajo del α sevane energije, zrcalijo del r in prepuščajo del d:

Thus, for a blackbody $\varepsilon_c = a_c = 1$, i.e. it only absorbs the irradiated energy without reflecting or permeating it. Bodies not having blackbody properties, absorb the part a of the irradiated energy, reflect the part r and permeate the part d, thus:

$$a + r + d = \varepsilon + r + d = 1 \quad (5).$$

Glavnina fizikalnih teles je neprepustna za IR sevanje ($d = 0$), toda zaradi $r > 0$ je koeficient sevanja ε manjši od ena. Taka telesa imenujemo siva telesa, njihovo sevanje pa je sestavljeno iz njihovega lastnega sevanja, ki je določeno z njihovo temperaturo glede na (3), in odbojnim sevanjem, ki je določeno z okoliškimi telesi.

Z merjenjem sevalne energije telesa in z upoštevanjem omenjenih zakonov, je mogoče določiti temperature teles brez dotikov. Te meritve so osnova termografske metode.

The majority of physical bodies are untransparent for IR radiation ($d = 0$), but because of $r > 0$ their emissivity coefficient ε is less than unity. Such bodies are called gray bodies, and the radiation from their surfaces consists of their own radiation determined by their temperature according to (3) and of the reflected radiation determined by the temperature of the surrounding bodies.

By measuring the radiated energy from a surface, and by taking into account the mentioned laws, the determination of surface temperatures becomes possible without the need to make contact with it. Such measurements are the basis of thermographic methods.

1 TERMOGRAFASKE NAPRAVE

Termografske metode delajo IR sevanje vidno, po drugi strani pa omogočajo določevanje temperaturne porazdelitve po površinah teles. Razvite so bile (večinoma v vojski) za omogočanje “vidnosti v temi” in v zadnjih tridesetih letih so na voljo tudi za množično uporabo. Termografske naprave so majhne kot video kamere in omogočajo snemanje temperaturnih porazdelitev v dejanskem času z ločljivosti, ki je boljša od 0,1°C. Rezultat meritev je termogram, ki predstavlja površinsko temperaturno porazdelitev v sivi skali ali v barvah. Termogram je viden na zaslonu naprave in ga lahko shranimo v pomnilnik za kasnejšo uporabo.

Termografski sistem je iz treh glavnih delov: optični del, preoblikovalni del in zaslonski del. Optični sistem je iz leč, ki so prosojne za IR sevanje (običajno iz germanija ali silicija, ki so prosojne za valovne dolžine nad 1,8 μm oziroma 1μm). Starejše naprave imajo mehanski sistem z rotirajočimi prizmami ali poševnimi ogledali. Prizme morajo biti tudi IR prepustne, medtem ko morajo ogledala odbijati IR sevanje (polirano zlato ali s silicijem obložen aluminij).

Osrednji del spremembe signala je IR sevalno iskalo, do katerega vodimo sliko objekta. Moderni sistemi uporabljajo fotonska iskala, narejena iz sintetičnih polprevodniških kristalov (In-Sb, Hg-Cd-Te), v katerih se nosilci nabojev (elektroni) sprostijo pod vplivom IR sevanja različnih valovnih dolžin. Imajo zelo majhen odzivni čas, toda morajo biti v kriogenskih temperaturah, da se jim zveča občutljivost in da so zaščiteni pred toplotnimi motnjami okolice. Za hlajenje je bil najprej uporabljen tekoči dušik; sodobne naprave pa uporabljajo Peltierjeve celice. Glede na njihovo sestavo je

1 THERMOGRAPHIC DEVICES

Thermographic devices make IR radiation visible, and they enable the determination of the temperature distribution on the surfaces of bodies. They have been developed (mostly by the military) to enable “sight in the dark”, and not until the last thirty or so years have they been available for public use. Contemporary thermographic devices are as small as video cameras and permit recording of temperature distributions in real time with a resolution better than 0.1 °C. The measurement result is a thermogram, which depicts the surface temperature distribution in gray scale or in a colored code. The thermogram is visible on the display of the device, and it may be saved to the memory for later evaluation.

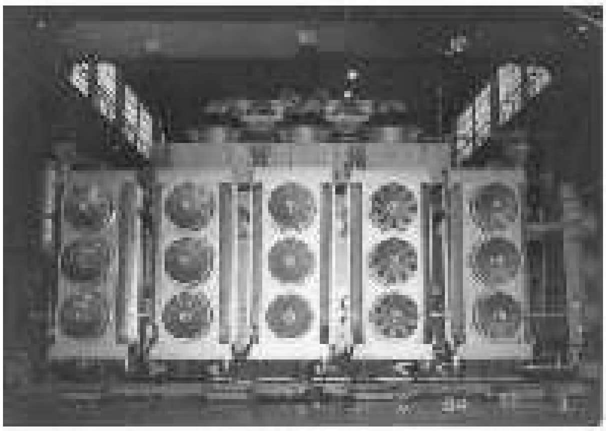
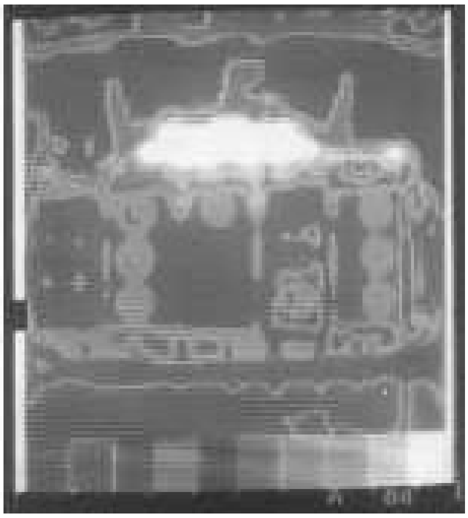
The thermographic system normally consists of three major parts: the optical, the converting and the displaying parts. The optical system consists of lenses transparent to IR (usually germanium or silicon, which are transparent to wavelengths above 1.8 μm or 1 μm respectively). Older devices had mechanical scanning systems with rotating prisms or tilting mirrors. Here the prisms also had to be IR transparent, while the mirrors had to reflect IR radiation (polished gold or silicon-coated aluminum).

The central part of the signal conversion is the IR radiation detector to which the object is focused by the optics. Modern systems use photon detectors made from synthetic semiconductor crystals (In-Sb, Hg-Cd-Te) in which the charge carriers (electrons) are set free under the influence of IR radiation of certain wavelengths. They have very short response times, but they have to be at cryogenic temperatures, in order to increase the sensitivity and to shield the thermal noise of the surroundings. For the cooling, liquid nitrogen was first used; modern devices use Peltier cells. Depending on their občutljivost zaznaval omejena na relativno ozke trakove valovnih dolžin (nekaj 5 μm), običajno v srednjem IR območju (2,5 do 50 μm). Občutljivost na krajše valovne dolžine so prednost pri višjih temperaturah in obratno. Sistem snemanja ima točkovna zaznavala, snemanje pa traja določen čas, za kolikor se izvedba termograma za določen časovni interval zakasni. Moderne naprave uporabljajo FPA tehniko (Focal Plane Array) z množico zaznaval. Standardna iskala FPA imajo 244 vrstic s 320 zaznavali, na področju 8 x 6 mm. Taka zaznavala so veliko hitrejša in omogočajo termografijo v dejanskem času. Ojačen in moduliran električni signal, ki ga daje zaznavalo, se prenese na zaslon termografske naprave.

Termogrami se običajno prikazujejo na zaslonu (katodna cev ali zaslon na tekočih kristalih) (sl. 3). Termogram je slika predmeta, ki predstavlja površinske temperature v lestvici sivih odtenkov. Moderne naprave lahko spremenijo sivo skalo v barvno, kar pomeni, da različne barve pomenijo različna temperaturna področja. Osnovna razlika med termogramom in fotografijo je, da termogram predstavlja sevano energijo poleg odbite energije. To je eden od največjih problemov temperaturnih meritev s termogrami. Če termogram naredimo na objektu z lastnostmi črnega telesa ($\varepsilon = \varepsilon_c = 1$), bi to pomenilo stanje telesa pri njegovi lastni temperaturi. Dejanski objekti pa so siva telesa, kar pomeni da njihovi termogrami vsebujejo delež, sorazmeren s koeficientom odboja $r = 1 - \varepsilon$ (za $d = 0$ - neprosojno telo), zrcalnega sevanja, ki prihaja iz okoliških teles z različnimi temperaturami. Koeficient oddaje je odvisen od površinskih lastnosti in kota oddaje glede na pravokotnico. To naredi stanje bolj zapleteno za nenavadne geometrijske oblike. Nekatere termografske naprave so prilagojene za sevanje črnega telesa, kar pomeni, da moramo izračunati natančno temperaturo telesa z uporabo podatka za sevalnost površine. Moderne naprave

composition, the detector sensitivity is bound to relatively narrow wavelength bands (some 5 μm), usually in the medium IR range (2.5 to 50 μm). Detectors sensitive to shorter wavelengths are preferred for higher temperatures and vice versa. Scanning systems have point detectors, and scanning takes a certain time, thus slowing the realization of the thermogram. Modern devices use Focal Plane Array (FPA) detectors with a multitude of detectors. Standard FPA detectors have 244 lines with 320 detectors each, with an area of 8 x 6 mm. Such detectors are much faster and enable real-time thermography. The amplified and modulated electrical signal produced by the detector is transferred to the display unit of the thermographic device.

The thermograms are usually displayed on a screen (cathode-ray tube or LC display) - Figure 3. A thermogram is a picture of the object, reproducing the surface temperature distribution in gray scale grades. Modern devices can convert the gray scale into a colored code, which means that different colors are associated with narrow gray scale regions. The basic difference between a thermogram and a photograph is that the thermogram represents the radiated energy of the object besides the reflected energy. This indicates one of the biggest problems of thermographic temperature measurements. If the thermogram was taken of an object with blackbody properties ($\varepsilon = \varepsilon_c = 1$), it would represent the state of the object determined by its own temperature. Real objects however, are graybodies, meaning that their thermograms contain a share, proportional to the objects' reflection coefficient $r = 1 - \varepsilon$ (for $d = 0$ - untransparent body), of reflected radiation coming from neighboring objects at different temperatures. The emissivity coefficient depends upon the surface properties and the emission angle to the surface normal. This makes the situation more complicated for complex geometrical shapes. Some thermographic devices are adjusted to blackbody radiation, thus making it necessary to calculate the exact temperature values by using data for the emissivity of the surfaces. Mod-

Sl. 3. *Fotografija in termogram istega objekta*
Fig. 3. *Photograph and thermogram of the same object*

so prilagojene za katerokoli sevalnost, toda to velja za celo področje snemanja.

Opisane lastnosti dokazujejo, da je termografija idealno sredstvo za kakovostno določanje temperaturne porazdelitve po objektnih površinah, toda merljivost rezultatov je povezana s številnimi problemi.

2 UPORABA TERMOGRAFIJE

Termografijo lahko razdelimo, glede na način merjenja, na pasivno in aktivno termografijo.

Pri aktivni termografiji je posneti objekt pri temperaturi, ki je različna od okolice, kar omogoča neposredno izdelavo termogramov brez posebnih priprav.

Pri aktivni termografiji je objekt enake temperature kakor okolica, kar pomeni, da moramo objekt toplotno stimulirati, da dobimo potrebni toplotni kontrast. To povzroča, da lahko aktivno termografijo uporabljamo predvsem v laboratorijskih prilikah.

2.1 Pasivna termografija

Uporaba pasivne termografije je zelo široka. Poleg industrijskih merjenj jo uporabljamo v medicini, biologiji, gradbeništvu, meteorologiji, varstva pred ognjem in pri iskanju izgubljenih ljudi v divjini. Pasivna termografija daje večinoma kakovostne termograme, ki so ugodni za primerjavo. Oblika temperaturnega področja termograma kaže na možnost nezveznosti.

Ena najpogostejših uporab termografije je nadzor in vzdrževanje industrijskih naprav. Značilen primer je ogled električne opreme. Slika 4 prikazuje grafično termografsko pripravo in termogram, ki označuje pregrevanje zaradi kratkega stika. Namestitev takega sistema povzroča

ern devices may be adjusted to any given emissivity, but this is constant for the entire recording area.

The described circumstances indicate that thermography is an ideal means for qualitative determination of the temperature distribution on object surfaces, but the quantification of the measurement results may be associated with serious problems.

2 APPLICATION OF THERMOGRAPHY

Thermography may be divided, according to the measuring approach, into passive and active thermography.

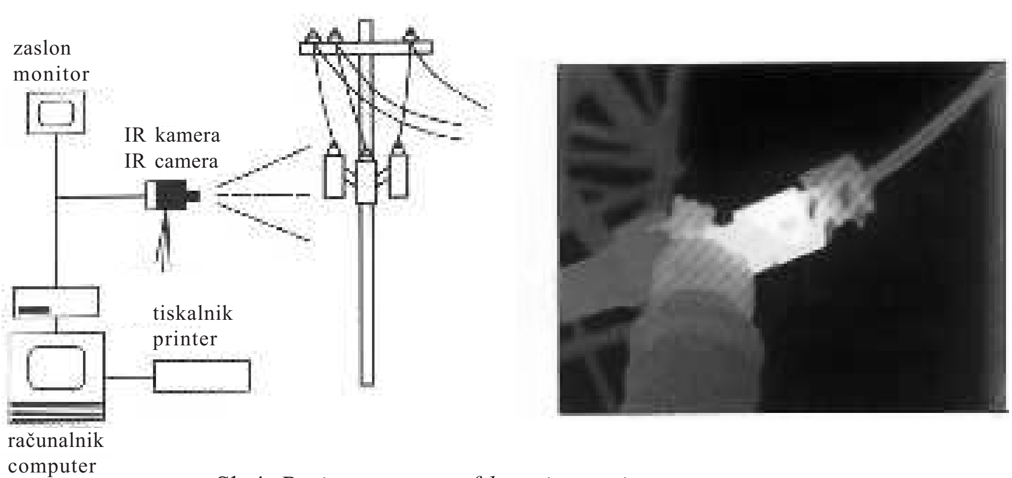
In passive thermography the recorded object is at temperatures that are different from the ambient, thus enabling direct taking of thermograms, without special preparations.

With active thermography the objects are at the ambient temperature, thus making necessary a thermal stimulation of the object in order to obtain the required thermal contrast. This makes active thermography possible mostly in laboratory applications.

2.1 Passive thermography

The application of passive thermography is very wide. Along with industrial measurements, it is used in medicine, biology, civil engineering, meteorology, fire protection, for the detection of people lost in the wilderness etc. Passive thermography gives mostly qualitative thermograms which are suitable for comparisons. The shape of the temperature field on the thermogram indicates the possible cause of the discontinuity.

One of the most frequent applications of thermography is in the supervision and maintenance of industrial facilities. A characteristic example is the inspection of electrical switching equipment. Fig. 4 shows a schematic of the thermographic inspection gear and a thermogram indicating overheating due to a short cir-



Sl. 4. *Pasivna termografska priprava in termogram*
Fig. 4. *Passive thermography arrangement and thermogram*

naraščanje produktivnosti in učinkovitosti obrata, ker omogoča odstranitev nenačrtovanih motenj in skrajša čas popravil.

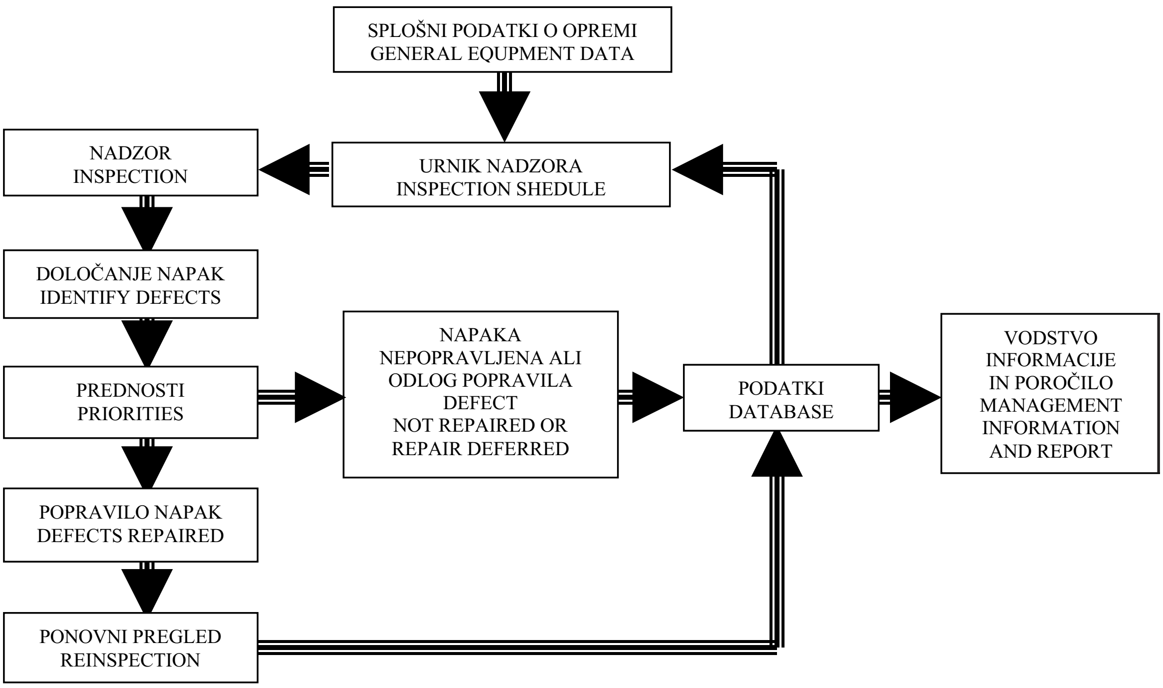
Nadzor nad večino proizvodnih naprav lahko organiziramo glede na pretočni diagram na sliki 5. Podatki vsebujejo seznam delov, ki jih nadzorujemo, z opisom pomena, razpoložljivosti nadomestnih delov, pričakovane dobe trajanja, vprašanj o varnosti in njihove lege v sistemu. Urnik nadzora je narejen na podlagi domnev in začetnih pregledov, medtem ko se nezadostnosti določajo in razvrščajo glede na izločitveno teorijo (takojšnje popravilo, načrtovano popravilo v prihodnosti ali podaljšano nadzorstvo).

To je opravljeno na podlagi razpoložljivih rezervnih delov, postopkov vzdrževanja in ocene nenačrtovanih zastojev. Odločitve in podatki o napakah se shranijo v bazo. Urnik nadzorov in baza podatkov sta tako stalno dopolnjevana s podatki iz nadzorov. V tem postopku se lahko zgodi, da nekaterih pomanjkljivosti ne moremo odpraviti zaradi nedostopnosti opreme itn., nepopolnosti sekundarnega izvora, napak v instalacijah, napačnih ureditev in izvedb napak. Urnik mora prav tako vsebovati informacije, ki jih potrebujemo za nadzor v prihodnosti, npr. poraba časa, tipi popravil in število rezervnih delov. Te podatke potrebujemo tudi za shranjevanje rezervnih delov in kot informacijo za časovno dobo komponent. Po prvih uvajalnih obdobjih opisani sistem dosega zmanjšanje števila zlomov in napak, posebno najbolj nevarnih, podatki pa omogočajo razvoj službe vzdrževanja.

cuit. The installation of an inspection system in such cases results in increased productivity and efficiency of the facility, because it eliminates unplanned operation interruptions and shortens the repair period.

The supervision of most production facilities may be organized according to the flow diagram in Fig. 5. The equipment data contains the list of the system parts under supervision, with the description of their importance, availability of spare parts, expected life time, security requests and their position in the system. The inspection schedule is prepared on the basis of prediction and initial inspection, where deficiencies are identified and sorted according to elimination priority (immediate repair, planned repair in the future or extended surveillance).

This is done on the basis of disposable spare parts, maintenance procedures and an estimation of unplanned standstill. The decisions made and the data on failures are loaded to the data base. The inspection schedule and the data base are thus permanently updated with data from successive inspections. In this procedure it may occur that some failures may not be eliminated because of inaccessibility of the equipment etc., and imperfections of secondary origin, due to faulty installation, wrong adjustment or manufacturing errors, may be indicated. The schedule must also contain a series of information needed for future inspections, such as time consumption, types of repair and the number of spare parts. This data is also used for the spare part storage and gives information on the life time of components. After the initial running-in period, the described system results in a decreased number of breakdowns and failures, especially the most dangerous ones, and the data base yields elements for the development of the maintenance service.



Sl. 5. *Diagram poteka nadzora dejavnosti*
Fig. 5. *Flow diagram of inspection activities*

2.2 Aktivna termografija

Z aktivno termografijo (sl. 6) objekt izvzamemo iz toplotnega ravnovesja z okolico s številnimi toplotnimi spodbudami (sunkovitimi, ponavljajočimi, zaprtimi, vibracijskimi) z namenom, da naredimo sklepe v zvezi z mehanskimi in fizikalnimi lastnostmi ali njihovo notranjostjo, medsebojnimi vplivi med objektom in okolico zaradi spremembe temperature.

Tipični primer aktivne termografije je aplikacija pri neporušnih testiranjih. Slika 7 prikazuje enega od številnih termogramov površine jeklene plošče s krožnimi nevidnimi vdolbinami. Temperaturna porazdelitev na površini je bila posneta za več določenih časov z zaprto termografijo, velikost vdolbin pa je bila izračunana z ustreznimi numeričnimi postopki [2].

V takih primerih je odločilna natančnost merjenja temperature. Določiti je treba sevanje površine telesa in poznati temperaturo okolice. Zato je treba opisan primer in podobne naloge izvajati v laboratoriju, kjer lahko nadziramo vse parametre.

V laboratorijskih razmerah lahko določimo tudi koeficient sevanja. To naredimo s termogrami površin pri znanih temperaturah, ki jih dosežemo z natančnim merjenjem temperature ali s puščanjem predmeta na znani temperaturi okolice daljši čas. Da se izognemo problemom določanja sevanja, v nekaterih primerih, kjer je to mogoče, predmet oblečemo s plastjo znane sevalnosti.

Aktivna termografija je tudi zelo uporabno orodje na področjih razvoja izdelkov, raziskovanja prenosa toplote, vizualizacije tokov in številnih drugih primerov.

2.2 Active thermography

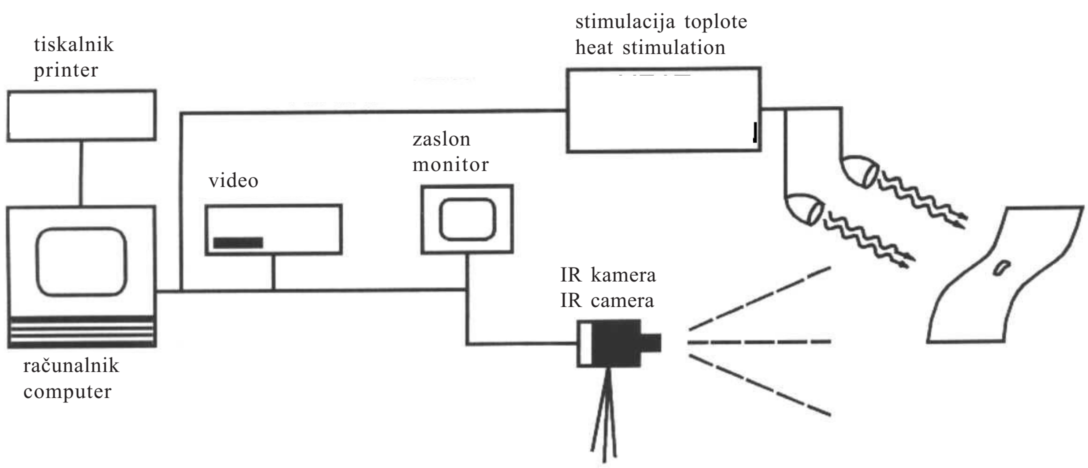
In active thermography, Fig. 6, the object is brought out of thermal balance with the ambient by various means of thermal stimulation (impulse, periodical, lock-in, vibration), in order to make conclusions on material and physical properties of its interior or on the patterns of interactions with the ambient, due to the induced temperature change.

A typical example of active thermography is its application in nondestructive testing. Fig. 7 shows one of a series of thermograms of the surface of a steel plate with circular recesses of variable depth on the invisible side. The temperature distribution on the surface was recorded for several defined time instants by means of lock-in thermography, and the size of the recesses was calculated using appropriate numerical procedures [2].

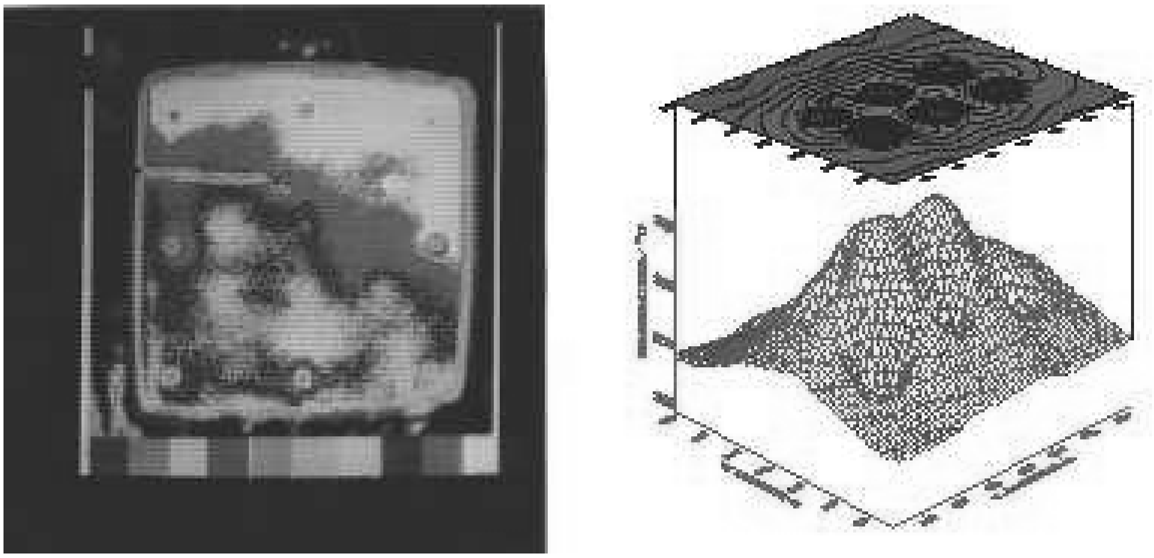
With such problems, the precision of the temperature measurement is crucial. As mentioned before, the emissivity of the object surface has to be exactly defined, and the temperature of the surrounding objects known. Therefore, the described example and similar tasks have to be carried out in the laboratory, where complete control of the relevant parameters is given.

In laboratory conditions even the emissivity coefficient may be determined by thermography. This is done by taking thermograms of surfaces at known temperatures, which is established by precise contact temperature measurements or by exposing the object to known temperature ambients for a long time. To avoid problems with unknown emissivity, in some cases, where it may be permitted, the object is coated with a layer of known emissivity coefficient.

Active thermography is also a very useful tool in other areas such as product development, research in heat transfer, flow visualization and many others.



Sl. 6. *Razporeditev pri aktivni termografiji*
Fig. 6. *Active thermography arrangement*



Sl. 7. *Termogram in tridimenzionalni prikaz izoterme plošče s presledki*
Fig. 7. *Thermogram and 3D isotherm presentation of plate with discontinuities*

3 SKLEP

Uporabnost termografije pri ekspertnih in znanstvenih dejavnostih je zelo široka. Zaradi njenih prednosti je termografija našla mesto v industriji, gradbeništvu, medicini, biologiji, meteorologiji itn. Glavne prednosti termografije so:

– merjenje temperature poteka brez stika s predmetom, s čimer se izognemo motnjam toplotnega stanja, kar je primer pri stikalnih meritvah;
– termogram je trajen posnetek temperaturnih vrednosti in porazdelitve na površini, ki jo zazna termografska naprava.

Seveda pa je treba omeniti tudi nekatere slabe strani termografije:

– natančnost meritev je odvisna od zanesljivosti podatkov o sevanju merjenih predmetov;
– če vzamemo termogram površine z nizkim sevalnim koeficientom, se lahko pojavijo motnje sevanja iz okolice, predvsem sončnega sevanja. Te težave postanejo izrazite pri kolikerostnih meritvah in jih lahko odpravimo samo v laboratorijih.

3 CONCLUSION

The applicability of thermography in expert and scientific activities is very wide. Due to its favorable features, thermography has found its place in industry, civil engineering, medicine, biology, meteorology etc. The basic advantages of thermography are:

– The temperature measurement is performed without contact with the object, thus avoiding the disturbance of the original thermal state, which is the case with contact temperature measurements.
– The thermogram is a lasting record of the temperature value and its distribution at the surfaces seen by the thermographic device.

However, some drawbacks of the thermographic method must be mentioned also:

– The quantitative accuracy of the measurements depends on the reliability of the emissivity data of the objects measured.
– When taking thermograms from surfaces at low emissivity coefficients, considerable disturbances from reflected radiation from surrounding objects may occur, especially from solar radiation. These difficulties become significant for quantitative measurements, and they may be overcome only in laboratory conditions.

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Tehnologije toplotnih črpalk

Heat-Pumping Technologies

Hermann Halozan

Človeštvo ima v sedanjem času številne probleme: rast števila svetovnega prebivalstva, predvsem v deželah v razvoju, spremembe klime zaradi spuščanja CO_2 v ozračje z gorenjem fosilnih goriv in drugih plinov, ki povzročajo učinek tople grede, in tanjšanje ozonske plasti. Tehnologije toplotnih črpalk, to je hlajenje, klimatizacija in toplotne črpalke, ki so večinoma nepoznane in težko razpoznavne za široke množice, imajo možnost za zmanjševanje negativnih vplivov predstavljenih problemov. Izboljšati je treba znanje ljudi o teh sistemih. Te tehnologije so zanesljive, energijsko učinkovite, prijetne za okolje, v uporabi so kjerkoli po svetu in njihova industrija obrne le 10% manj denarja od avtomobilske industrije. Tehnologija toplotnih črpalk je tudi ključna tehnologija za dosego ciljev Kyotskega vrha.

(Ključne besede: črpalke toplotne, razvoj črpalk, hladiva, vplivi na okolje)

Mankind presently has serious problems, the growth of the world population primarily in the developing countries, the expected climate change due to polluting the atmosphere with CO_2 from burning fossil fuels and other greenhouse gases, and ozone depletion. Heat-pumping technologies, i.e. refrigeration, air conditioning, and heat pumps, more or less unknown and hardly recognised by the public, have the potential for reducing the negative effects resulting from these boundary conditions. But the public awareness of these technologies has to be improved. Heat-pumping technologies are reliable, energy efficient, and environmentally friendly, they are in use world wide and the turn-over of the related industry is only 10 % less than the turn-over of the automotive industry. Heat pumping is one of the key technologies required to achieve the targets set at the Kyoto summit.

(Keywords: heat pumps, pump development, refrigerants, environmental effects)

0 UVOD

Človeštvo ima v sedanjem trenutku tri glavne probleme, ki so medijsko zelo zanimivi: najbolj resen je tanjšanje ozonske plasti, ki povzroča kožnega raka in uničuje biosfero morja; naslednji je globalno ogrevanje ozračja, tretji pa je hitra rast človeškega prebivalstva. Resnica je, da moramo spremeniti vrstni red teh problemov. Rast števila prebivalstva je največji problem, sledi mu ogrevanje ozračja, ki je posledica vedno večje rabe energije.

Tehnologije toplotnih črpalk, tj. hlajenje, klimatizacija in toplotne črpalke, ne morejo rešiti problema naraščanja števila prebivalstva. Imajo pa možnost za zagotovitev zalog hrane s hlajenjem, zagotovitev ugodja in higienskih razmer s klimatizacijo in zmanjšanje rabe energije posredno z odpravljanjem kvarjenja hrane in neposredno z uporabo proste energije in odpadne toplote za zagotovitev uporabne toplote s toplotnimi črpalkami z dodajanjem eksergije prosti anergiji.

0 INTRODUCTION

Mankind has three major global problems. According to the media, the most serious problem is ozone depletion resulting in skin cancer and the destruction of the biosphere of the sea. The second problem relates to global warming and the expected climate change, and the third is the rapid growth of the world population. However, in reality we should change the order of these problems. The growth of the world population is the main problem, followed by global warming as a consequence of this growth and the increased energy consumption, which goes hand in hand with these changes.

Heat pumping, i.e. refrigeration, air conditioning and heat pump technologies, cannot solve the problem of the growth of the world population, but it has the potential for ensuring food supply by utilising refrigeration, providing comfort and hygienic conditions by supplying heating and cooling as well as humidification and dehumidification depending on the climatic conditions. Heat pumping can indirectly reduce the energy demand by avoiding the spoilage of food as well as directly by utilising free energy and waste heat to provide useful heat by means of heat pumps adding exergy to the collected anergy.

1 ZGODOVINA TEHNOLOGIJ TOPLOTNIH ČRPALK

Toplotne črpalke so stara tehnologija. Leta 1824 je Carnot odkril teoretične osnove toplotnih črpalk, tj. obrnitev naravnega toka toplote od višje temperature k nižji z dodajanjem visoko vredne energije; proces, ki je rezultat tega, se lahko uporablja tako za pridobivanje toplote kakor tudi hladu. Zanimivo je, da se je to zgodilo še preden sta bila oblikovana prvi in drugi zakon termodinamike.

Leta 1835 sta Perkins in Evans neodvisno drug od drugega razvila prvi parni kompresorski hladilnik, kar je bilo začetek uporabe mehanskih hladilnih tehnologij za hranjenje živil. Kmalu je sledila namestitev prve toplotne črpalke. Leta 1855 je Peter Ritter pl. Rittinger oblikoval, glede na zapiske Carnota, izvedel in preskusil prvi mehanski parni rekompresor (MVR) pri proizvodnji soli v Ebenseeju, zgornja Avstrija, kar je bila prva toplotna črpalka v obratovanju. Imela je tri centrifugalne kompresorje s celotno električno močjo 20 MW in hladilno število (HŠ) v obsegu od 12 do 16.

Razvoj toplotnih črpalk je šel naprej. Carre je iznašel absorpcijski krog z delovnim sredstvom amoniak/voda, Linde je znanstveno raziskoval parne kompresorske hladilnike in uvedel številna nova hladiva: npr. amoniak in CO_2 ter uvedel klimatizacijo. Willis Carrier, ki je bil zelo dejaven na tem področju, pa je postal oče te tehnologije; omogočil je možnost življenja v področjih z izrednimi klimatskimi razmerami.

Edini problem v teh časih so bila hladiva. Med najuspešnejšimi je bil amoniak, ki pa je strupen, neznosno smrdi in je pod določenimi pogoji gorljiv, SO_2, ki ga prav tako uporabljamo kot hladivo, je najbrž najbolj strupeno uporabljano hladivo, CO_2, ki je prevladoval do konca tridesetih let, je visokotlačen fluid, propan pa je eksploziven.

Tako se nihče ne more čuditi, da so CFC in HCFC, ki sta jih iznašla Midgely in Henne iz družbe Frigidaire, katero je kasneje kupil DuPont, začeli kot nestrupena in negorljiva »varna« hladiva vstopati in kasneje prevladovati na trgu. S temi hladivi je bila mogoča 30 barska tehnologija, predstavljena je bila hermetična oprema in s tem je tehnologija toplotnih črpalk, ki je bila do takrat na voljo samo za industrijsko uporabo, vstopila na novo področje, na področje hišnih naprav (pregl. 1). Na drugi strani je v velikih sistemih amoniak preživel, izginil pa je v alternativnih hladivinih procesih.

2 MONTREAL IN REZULTATI

Leta 1987 so tehnologije toplotnih črpalk prišle v obravnavo v Montrealskem protokolu

1 THE HISTORY OF HEAT PUMPING TECHNOLOGIES

Heat pumping is an old technology. In 1824 S. Carnot described the theoretical basis for heat pumping, i.e. reversing of the natural heat flux from a higher to a lower temperature by adding high-grade energy; the process resulting from these considerations is suitable for producing both heat and cold. The interesting thing is that this idea was put forward before the first and second laws of thermodynamics were formulated.

In 1835, Perkins and Evans independently developed the first vapour-compression refrigeration machines, which was the beginning of the use of mechanical refrigeration technologies for food preservation. The first heat-pump installation soon followed. In 1855, Peter Ritter von Rittinger designed, built and operated the first mechanical vapour recompression MVR system (based on the work of Carnot) in the salt production plant in Ebensee, Upper Austria. This was the first heat pump in operation. At present there are three centrifugals with a total electric input of 20 MW and coefficients of preformance (COP) in the range of 12 to 16 in operation at this site.

The development of heat-pumping technologies continued with Carré's invention of the absorption cycle with an ammonia-water working pair. Linde investigated vapour-compression refrigeration cycles, he introduced several new refrigerants like ammonia and CO_2. Air conditioning was introduced, and Willis Carrier, who was very active in this field, became the father of this technology. Air conditioning offered the possibility to live in regions with extreme climatic conditions.

The only problem at this time were the refrigerants, the successful ones being ammonia, which is toxic, smells horrible, and under certain circumstances is flammable, SO_2, also used as a refrigerant, is probably the most toxic natural substance available, CO_2, which dominated marine refrigeration and air conditioning applications until the end of the thirties, is a high pressure fluid, and propane is explosive.

With this background nobody should be surprised that the CFCs and HCFC's developed by Midgely and Henne of the Frigidaire company - which was later bought by DuPont – were promoted as non-toxic and non-flammable "safety" refrigerants and later came to dominate the market. Using these refrigerants a common 30-bar technology was possible, hermetic equipment introduced, and heat-pumping technologies, suitable at this time only for industrial applications, entered a new field, the field of household appliances (Table 1). Of the old refrigerants, only ammonia survived for use in large systems, alternative cycles disappeared.

2 MONTREAL AND THE RESULTS

In 1987, heat-pumping technologies came under discussion through the Montreal Protocol on Subglede snovi, ki tanjšajo ozonsko plast. Osnovne raziskave sta opravila Molina in Rowlands. Rezultati so bili napoved tanjšanja ozonske plasti, posledica tega pa naraščanje števila kožnega raka ter uničevanje biosfere. Pokazana je bila tudi slika, ki prikazuje tanjšanje ozonske plasti (TOP - ODP) in možnost svetovnega segrevanja (MSS - GWP) za različna hladiva (sl. 1). Zanimiv je bil vir te slike tj. DuPont.

Tanjšanje ozonske plasti je bolj ali manj rešeno s sporazumi v Londonu in Kopenhagnu, CFC so že prepovedani v industrijskih državah, HCFC pa, ki so manj škodljivi ozonu, morajo biti izločeni do leta 2035, v Evropski zvezi do leta 2015. Evropska komisija v zadnjem času pospešuje te procese, v nekaterih evropskih državah so že realizirani. Toda to velja samo za industrijske države. Države v razvoju imajo veliko daljši čas za spremembo tehnologij iz CFC na HCFC in končno na hladiva brez klora. Morda lahko pride do problema, da bodo te tehnologije dosežene ne da bi bili odpravljeni HCFC.

stances that deplete the Ozone Layer. The basis was an investigation carried out by Molina and Rowlands, the results were predictions on the depletion of the ozone layer which would result in an tremendous increase in the rates of skin-cancer and the destruction of the biosphere. They produced a nice graph showing the ozone depletion potential (ODP) and the global warming potential (GWP) of different working fluids (Fig. 1). Interestingly, the source of this graph was DuPont.

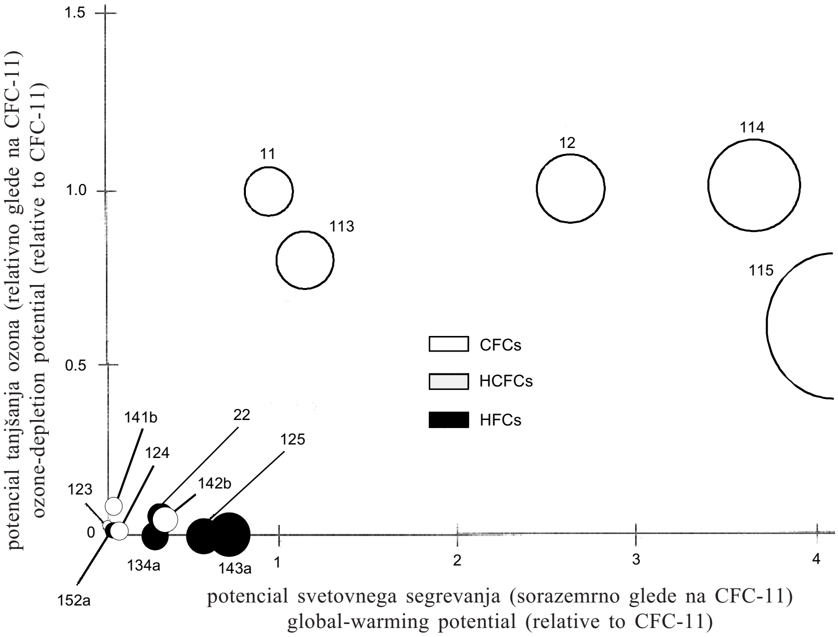
The problem of ozone depletion has been more or less solved by the follow-up agreements decided in London and in Kopenhagen with the result that CFCs are already forbidden in the industrialised countries and HCFCs, less harmful for the ozone layer, are to be phased out by 2035 or 2015 in the case of the European Union. And the Commission is currently considering an acceleration of this process, which has already been completed in some European countries. This situtation is only valid for the industrialised countries; the developing countries have a much longer time frame in which to change their technologies from CFCs to HCFCs and finally to chlorine-free fluids. It might become a problem if they go this way and do not omit the HCFC step.

Preglednica 1. *Okoljski vpliv hladiv*
Table 1. *Environmental Impact of Refrigerants*

oznaka nomenclature		lokalni vplivi local effects		svetovni vplivi global effects				
		gorljivost (koncentracija v zraku) flammability (concentration in air) (%)	strupenost toxicity	doba trajanja v atmosferi atmospheric life time (a)	TOP - ODP (potencial tanjšanja ozona - ozon depletion potential) (R-11 = 1)	MSS - GWP (potencial globalnega segrevanja - global warming potential - kg CO_2 /kg) časovno obzorje time horizon (a)		
						20	100	500
CFC								
R-11	($CFCl_3$)	-	5a	60	1,0	4500	3500	1500
R-12	(CF_2Cl_2)	-	6	130	1,0	7100	7300	4500
R-113	($C_2F_3Cl_2$)	-	4-5	90	1,07	4500	4200	2100
R-114	($C_2F_4Cl_2$)	-	6	200	0,8	6000	6900	5500
R-115	(C_2F_5Cl)	-	6	400	0,52	5500	6900	7400
R-500	(R12+R152a)	-	5a	-	ca. 0,7	5400	5400	3400
R-502	(R22+R115)	-	5a	-	ca. 0,2	4800	4300	4000
HCFC:								
R-22	(CHF_2Cl)	-	5a	15	0,055	4100	1500	510
R-123	($C_2HF_3Cl_3$)	-	-	2	0,02	310	85	29
R-124	($CHClFCF_3$)	?	?	7	0,022	1500	430	150
R-141b	(CCl_2FCH_3)	7,4..15,1	?	8	0,11	1500	440	150
R-142b	($C_2H_3F_2Cl$)	6,9..14,9	-	19	0,065	3700	1600	540
HFC								
R-23	(CHF_3)	-	?	310	0	-	-	12
R-32	(CH_2F_2)	14,6	?	16	0	-	650	220
R-125	(C_2HF_5)	-	?	28	0	4700	2500	860
R-134a	($C_2H_2F_4$)	-	?	16	0	3200	1200	420
R-143a	(CF_3CH_3)	7,1	?	41	0	4500	2900	1000
R-152a	($C_2H_4F_2$)	3,7..17,1	-	2	0	510	140	47
ostalo / others								
R-50	(CH_4)	4,9..15,0	5b	10	0	63	21	9
R-270	(C_3H_6)	2,0..11,1	?	-	0	3	3	3
R-290	(C_3H_8)	2,1..9,5	5b	-	0	3	3	3
R-600	(C_4H_{10})	1,5..8,4	5	-	0	3	3	3
R-600a	(C_4H_{10})	1,8..8,4	5b	-	0	3	3	3
R-717	(NH_3)	15,0..25,0	2	-	0	-	-	-
R-718	(H_2O)	-	6	-	0	-	-	-
R-744	(CO_2)	-	5	120	0	1	1	1
R-764	(SO_2)	-	1	-	0	-	-	-

Poleg tanjšanja ozonske plasti obstaja še en vpliv CFC in HCFC. To je njihov prispevek h globalnemu segrevanju z naraščajočim sevanjem, ki ga poznamo kot učinek tople grede. Za osnovo je bil vzet R-11, ki je prav tako podlaga za tanjšanje ozonske plasti.

Besides ozone depletion there is another global effect of CFCs and HCFCs, it is their contribution to global warming by increasing the radiative forcing of the natural greenhouse effect. This was originally expressed on the basis R-11, which has also been taken as a basis for ozone depletion.



Sl. 1. *TOP nasproti MSS za različne CFC, HCFC in HFC*
Fig. 1. *ODP versus GWP of different CFCs, HCFCs and HFCs*

Medtem ko tanjšanja ozonske plasti ne moremo izraziti na drug način, pa lahko potencial svetovnega segrevanja temelji na CO_2, kar nam daje primerjavo z ostalimi procesi kot je gorenje fosilnih goriv. Če vzamemo CFC-je in HCFC-je, alternative HFC-jev brez klora, potem se MSS meri v tisoč kilogramih CO_2, kar pa postane relativno glede na emisije 0,2 kg/kWh_t v primeru plina, 0,3 kg/kWh_t v primeru olja in 0,4 kg/kWh_t v primeru premoga. Če upoštevamo vse energijske porabe lahko ugotovimo, da je glavni povzročitelj klimatskih sprememb CO_2, ki se sprošča pri gorenju fosilnih goriv.

While ozone depletion cannot be expressed in another way, the global warming potential can also be based on CO_2, and this provides a connection to other processes like burning fossil fuels. For CFCs, HCFCs and the chlorine-free alternatives to HFCs the GWP is counted in thousands of kg of CO_2, but this becomes relatively small when considering CO_2 emissions of 0.2 $kg/kWh_{thermal}$ in the case of gas, 0.3 $kg/kWh_{thermal}$ in the case of oil and 0.4 $kg/kWh_{thermal}$ in the case of coal. In terms of global energy use the main contribution to the expected climate change will come from CO_2 as a result of burning fossil fuels.

3 ALTERNATIVNA HLADIVA

Sintetična hladiva brez klora kot nadomestek CFC in HCFC proizvajajo v kemični industriji kot hidrofluorokarbonati – HFC – R134a, R-125, R-32 in R143a. Samo R134a se lahko uporablja kot nadomestek R-12, slabše v nizkotemperaturnem območju, boljše v visokotemperaturnem območju, do 84 EC temperature kondenzacije. R-32 in R-143a, obe izvrstni hladivi, sta vnetljivi, R-125 pa ima termodinamične lastnosti, ki onemogočajo, da ga uporabljamo kot čisto hladivo. Rezultat so zmesi, pri katerih R-134 in R-125 uporabljamo za zadušitev vnetljivosti. Takšne zmesi so R-404 in R-507 kot

3 ALTERNATIVE WORKING FLUIDS

The synthetic, chlorine-free alternatives to CFCs and HCFCs provided by the chemical industry are the hydrofluorocarbons HFCs R-134a, R-125, R-32 and R-143a. But only R-134a can be used as a pure fluid alternative to R-12, worse in the low-tempertaure region, better in the high-temperature region up to the 84 ^{O}C condensing temperature. R-32 and R-143a, both excellent refrigerants, are flammable, and R-125 has thermodynamic properties which make it unsuitable to be used as a pure refrigerant. The result are mixtures, where R-134a and R-125 are used to suppress flammability. Such mixtures are R-404A and R-507 as alternatives for R-502, R-407C as an alternadomestek za R-502 in R-407C kot nadomestek za R-22. Pravkar pa prihaja na trg R-410A, ki je zelo učinkovito hladivo in ustreza 40 barni tehnologiji.

Poleg tega da je večina teh nadomestkov neazeotropnih, imajo veliko zmožnost segrevanja ozračja, ker bo postalo naslednja tema razprav tehnologij toplotnih črpalk.

Naslednja možnost je vpeljava naravnih hladiv, npr. amoniak (R-717), ogljikovodiki propan (R-290), propilen (R-1270), ali izobutan (R-600a), voda (R-718) in CO_2 (R-744). Amoniak in ogljikovodiki ne zadostujejo zahtevam po varnih hladivih zaradi strupenosti in gorljivosti; voda in CO_2 pa sta varni hladivi [5].

Toda CFC niso mogli nadomestiti starega hladiva amoniaka (R-717) v celoti; v številnih hladilnih sistemih je bil amoniak vedno prva izbira, ker je odlično hladivo, je poceni v primerjavi s (H)CFC in je prijeten za okolje. Obstajajo seveda nekatere pomanjkljivosti: amoniak je strupen in njegov vonj, ki je zelo značilen, lahko povzroči paniko. Baker ne reagira z amoniakom in običajno se uporabljajo odprti kompresorji. Amoniak ima naraščajoč delež v novi opremi, razvoj gre naprej z namenom zmanjševanja deleža hladiva v sistemu.

Ogljikovodiki so dosegli najmanj en uspeh, izobutan ali zmesi propana in izobutana se uporabljajo kot hladiva v hladilnikih in zamrzovalnikih. Propan pa ima še eno odliko: je odlično nadomestilo za R-22, če pa uporabimo notranji prenosnik toplote, postane še bolj učinkovit kot R-22 z enako hladilno močjo [6]. Problem propana je omejevanje proizvajalcev kompresorjev, kaže, da je v ZDA nekaj izdelovalcev, ki hočejo preprečiti uporabo propana in propilena.

Voda se je in se zelo uspešno uporablja v sistemih MVR; dandanes se uporablja tudi pri hladilnikih, pri katerih je voda hladivo in nosilec toplote. Zaradi majhne prostorninske hladilne moči uporabljamo centrifugalne kompresorje, najnižja izvedena moč pa je 1 MW.

Zelo zanimivo hladivo je CO_2. Naravno hladilno sredstvo CO_2 (R-744), ki ga je uvedel Linde leta 1881, je postalo pomembno hladivo (sl. 2). Uporabljano je bilo do konca tridesetih let kot hladivo za hlajenje na ladjah in za klimatizacijo v stavbah, v obeh primerih torej, ko je potrebno »varno« hladivo. Težave povzročajo termodinamične lastnosti CO_2; kritične vrednosti so 31 °C in 74 bar. To se dogaja predvsem pri višjih temperaturah v območju kritičnih vrednostih, kjer se bistveno zmanjšata moč in izkoristek.

Za CO_2 obstajajo in bodo še obstajale v prihodnosti številne uporabe, ki so nadgradnja

native for R-22 and, just entering the market, R-410A. Although a very efficient working fluid, R-410A requires a 40-bar technology.

The majority of these alternatives are non-azeotropic mixtures, they also have a high global-warming potential, and this will become, after ozone depletion, the next topic of the discussion on the global impact of heat-pumping technologies.

Another possibility, however, is switching back to the old "natural" refrigerants like ammonia (R-717), the hydrocarbons like propane (R-290), propilene (R-1270) and isobutane (R-600a), water (R-718), or CO_2 (R-744). Ammonia and the hydrocarbons do not meet the requirements of a "safety" refrigerant because of toxicity and/or flammability, but water and CO_2 are safety refrigerants [5].

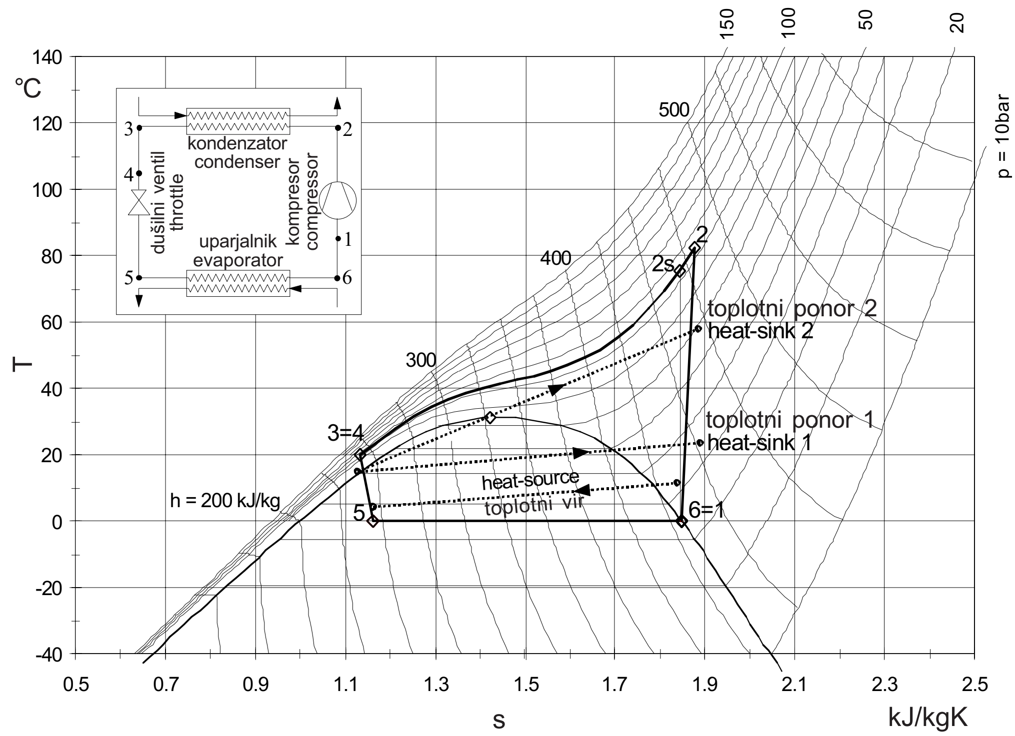
Not even CFCs have been able to completely replace the old refrigerant, ammonia (R-717). In large refrigeration systems ammonia has always been the first choice because it is an excellent refrigerant, it is cheap compared with the (H)CFCs, and it is environmentally benign. But there are some disadvantages: ammonia is toxic, and its characteristic smell, which acts as a warning signal, can cause panic. Copper is not compatible with ammonia, and open compressors are usually used. Nevertheless, ammonia has an increasing share in new equipment where developments are underway to reduce the refrigerant charge of the systems.

The hydrocarbons have achieved at least one success, isobutane or mixtures of propane and isobutane are used as refrigerants in refrigerators and freezers. But propane has another feature: it is an excellent substitute for R-22, and using an internal heat exchanger it becomes even more efficient than R-22 with about the same cooling capacity [6]. One problem associated with propane are the restrictions made by compressor manufacturers, and it seems that at least one large compressor manufacturer in the USA wants to prevent the use of propane and propilene.

Water has been and is being used successfully in MVR systems; but nowadays it is also used for chillers where water is both refrigerant and heat carrier. Due to the low volumetric cooling capacity centrifugals have to be used, and the smallest capacity presently realised is about 1 MW.

A very interetsing refrigerant is CO_2. The "natural" working fluid CO_2 (R-744), introduced by Linde in 1881 (Fig. 2), was used until the end of the thirties as a refrigerant for marine cooling and for air-conditioning systems in buildings, both applications where a "safety" refrigerant was required. Difficulties were caused by the thermodynamic properties of CO_2, the critical data are about 31^{O}C and 74 bar. This resulted in a trans-critical operation where both capacity and efficiency dropped significantly at high ambient temperatures.

For CO_2 there is an increasing number of applications which are superior to the present solutions with respect to the environment and also with



Sl. 2. *Diagram temperatura/entropija za CO_2 s pod- in z medkritičnim krogom*
Fig. 2. *Temperature/Entropy Diagram of CO_2 with a sub-critical and a trans-critical cycle*

sedanjih rešitev z vidika varovanja okolja in učinkovitosti [7]. Kot primer lahko navedemo spremembe v uparjalniškem sistemu hlajenja sekundarnega kroga za zmanjšanje polnjenja s hladivi, primeri ko se ne moremo izogniti izgubam hladiva in nove uporabe z višjimi učinkovitostmi, ki jih lahko dosežemo z uporabo tega hladiva.

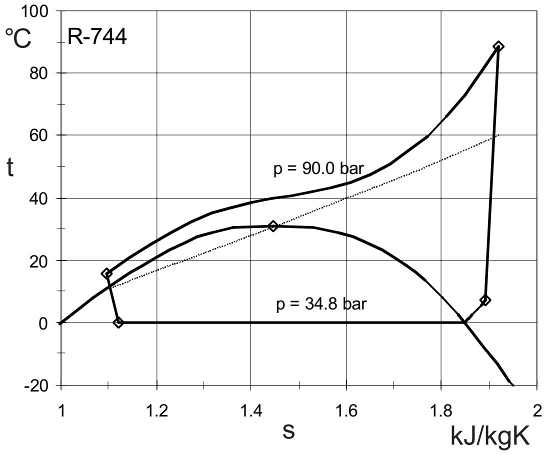
Uporabljamo ga tudi za priredbe toplotnih črpalk s temperaturami kondenzacije nad 30 °C, kar je predlagal prof. Lorentzen, s tlaki do 140 bar [8]. Ta krožni proces je označen z uparjanjem v podkritičnem področju in s kondenzacijo v nadkritičnem področju. Raziskujejo in testirajo se premične klimatizacijske naprave, posebno dvojen naprave imajo določene prednosti pred drugimi. Za pripravo tople vode (sl. 3), hladilnike zraka in rekuperatorje toplote [2], za sušilnike in razvlaževalnike je CO_2 v prednosti pred konvencionalnimi sistemi. Resnični problem CO_2 ni tehnologija, pač pa dostopnost komponent v velikih količinah po zmernih cenah. CO_2 ni in ne bo zdravilo, ki lahko reši probleme pri hlajenju, klimatizaciji in toplotnih črpalkah, toda za posebne primere je najboljša rešitev.

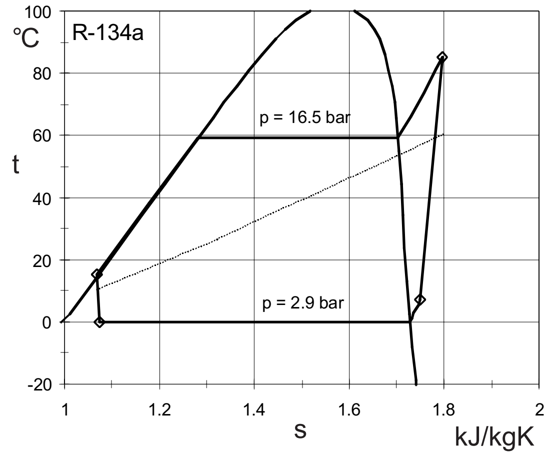
Izbirni kriteriji za hladiva morajo obsegati izkoristek, varnost in okoljsko sprejemljivost. Glavni problem je izkoristek, ker to pomeni energijsko porabo in le to moramo zmanjšati. Varnost je seveda zelo pomembna, toda problem varnosti lahko rešimo z uporabo ustrezne tehnologije. Dokaz "dodatne nevarnosti", ki se uporablja v novih sistemih, ni

respect to efficiency [7]. Examples are the change from direct evaporation systems in refrigeration to secondary loop systems for reducing the refrigerant charge, applications where refrigerant losses cannot be fully avoided, and new applications with higher efficiencies, which can be achieved by utilising CO_2 and the cycle characteristic.

For heat-pump applications with condensing temperatures exceeding 30 ^{O}C the transcritical cycle, also proposed by the late Prof. Lorentzen, with pressures up to 140 bar has to be used [8]. This cycle is characterised by evaporation taking place in the sub-critical region, whereas heat rejection occurs in the super-critical region. Mobile air conditioning is being investigated and tested in depth, stationary air conditioners, especially dual-mode systems, also show advantages. For once-through hot-water production (Fig. 3), air-heating and heat-recovery systems [2], drying as well as dehumidification processes, CO_2 is superior to the conventional processes. The real problem of CO_2 is not the technology, but the availability of components produced on a large scale for a reasonable price. CO_2 is not and will not be a cure-all which solves all the problems of refrigeration, air conditioning, and heat pumps, but for special applications it is an unbeatable solution.

Selection criteria for refrigerants have to cover efficiency, safety and environmental acceptability. The main point is efficiency, because efficiency means energy requirement, and energy requirement has to be minimized. Safety is of course important, but the problem of safety can be solved by using the appropriate technology, and the argument of the additional risk which is often used for new





Sl. 3. *Grelnik vode s toplotno črpalko 10 do 60°C* COP_{co2}*=4,6,* $COP_{R\text{-}134a}$*=4,0*

Fig. 3. *Heat Pump Water Heater 10 to 60°C* COP_{co2} *= 4.6,* $COP_{R\text{-}134a}$ *= 4.0*

pravilen, dokler sistem deluje v veliko višjem nevarnem nivoju.

4 VPLIV TEHNOLOGIJ TOPLOTNIH ČRPALK

Toplotne črpalke so preskušena in zanesljiva tehnologija. V primeru proizvodnje hladu za zmrzovanje, klimatizacijo, za medicinske in industrijske procese nimajo konkurence. Za proizvodnjo toplote morajo toplotne črpalke tekmovati z običajnimi proizvajalci toplote s sežiganjem goriv, največkrat fosilnih.

Toplotne črpalke so energijsko učinkovita in za okolje prijetna tehnologija [1]. Ponujajo možnost prestavitve energije okoliškega zraka, vode ali tal oziroma odpadne toplote na temperaturni nivo, ki ustreza ogrevanju zraka, za proizvodnjo tople vode in tudi za industrijske procese, in sicer tako, da dodajajo majhen del zelo vredne energije, imenovane eksergije, k prosti energiji. Primerjava toplote iz toplotnih črpalk z običajnimi postopki pokaže, da s toplotnimi črpalkami lahko porabo primarne energije zmanjšamo za polovico.

Tehnologija toplotnih črpalk je uporabna povsod po svetu. V tem trenutku deluje okoli 120 milijonov enot s toplotno močjo 800 TWh/a, ki zmanjšujejo emisijo CO_2 za 0,12 Gton/a. Potencial za zmanjšanje emisij CO_2 v stanovanjskem področju s 30% je okoli 6% celotnih emisij na svetu, ki znašajo 20 Gton/a. To je eden največjih možnosti za zmanjšanje CO_2. Zato so toplotne črpalke ena glavnih tehnologij za zniževanje emisij CO_2, ki izhajajo iz gorenja fosilnih goriv in ustrezajo ciljem Kyotskega protokola [3].

Problem je v tem, da samo 5 odstotkov teh toplotnih črpalk deluje v Evropi in če se osredotočimo samo na naprave za ogrevanje, je število okoli 1,2 milijona enot. To pomeni, da je Evropa glede toplotnih črpalk dežela v razvoju, ker prezira prednosti te tehnologije.

systems is not correct as long as applications exist with a much higher endangering potential.

4 THE IMPACT OF HEAT PUMPING TECHNOLOGIES

Heat pumping is a proven and reliable technology. For producing cold for refrigeration, air conditioning, medical and industrial processes it has no competitor. For producing heat as heat pumps it has to compete with conventional heat produced by burning fuels, mostly fossil fuels.

Heat pumps are an energy-efficient and environmentally friendly technology [1]. They offer the possibility to shift free energy from outdoor air, water or ground and waste heat to a temperature level required for space heating, hot-water production, but also for industrial processes, adding small amounts of high-grade energy, today called exergy, to the free energy. Comparing heat delivery by heat pumps with conventional methods, i.e. burning fossil fuels, one can easily show that with heat pumps the primary energy consumption can be at least cut in half.

Heat pumping is a technology used world wide. Presently, about 120 million units with a thermal output of 800 TWh/a are in operation, reducing CO_2 emissions by 0.12 Gt/a. The potential for reducing CO_2 emissions with a market share of 30 % in the building sector is about 6 % of the total world-wide CO_2 emissions of 20 Gt/a. This is one of the largest CO_2-reduction potentials for a single technology. Consequently, heat pumps are one of the key technologies for reducing CO_2 emissions resulting from burning fossil fuels and meeting the Kyoto targets [3].

The problem is that only about 5 % of these heat pumps are running in Europe, and if one concentrates on heating-only devices, the number is only in the range of 1.2 Million units. This means that in terms of heat pumps, Europe is a developing country neglecting the advantages of this technology.

5 SKLEPI

Ključ za usklajeni razvoj v energetskem trženju je izogibati se uničevanja okolja. Že leta 1824 je Sadi Carnot odkril termodinamična pravila za tehnologije toplotnih črpalk in je s tem tudi spremenil prvi in drugi glavni zakon termodinamike, ki sta ju formulirala leta 1842 Robert Mayer in 1950 Clausius. Če zasledujemo pogovore o energiji danes, si lahko mislimo, da Carnot in Clausius nista nikoli obstajala.

Ali (H)CFC resnično tanjšajo ozonsko plast, je še vedno vprašanje. Posledice naraščanja koncentracije toplogrednih plinov, kakor sta CO_2 in CH_4 v atmosferi, so, posebej za daljše obdobje, dobro poznane iz knjig o Greenlandskem ledu: preskusi na ledu kažejo, da naraščanje koncentracije CO_2 povzroča zvišanje povprečne temperature na našem planetu in s tem klimatske spremembe. To pomeni, da moramo previdno uporabljati fosilna goriva in jih moramo izkoriščati učinkoviteje. Toplotne črpalke so ena od tehnologij za dosego tega cilja.

"Uspeh na trgu ni pojav, je rezultat raziskav, odličnih izdelkov, izšolanih inštalaterjev, pomoči ustanov in političnih ciljev"

Če ne pozabimo teh dejstev, če vlada sprejme pomen te tehnologije in če obstaja resnična potreba po zmanjšanju emisij CO_2, potem se bodo toplotne črpalke uveljavile tudi v Evropi in prispevale k boljši prihodnosti. Od časa je odvisno, ali bomo dosegli Kyotske cilje, širili znanje in povečevali zavest za toplotne črpalke kot energijsko učinkovito in okolju prijazno tehnologijo v Evropi. En cilj še ni bil dosežen: to je cilj prepričati politike.

5 CONCLUSIONS

The key to sustainable development and rational energy management is avoiding the destruction of our environment. In 1824 Sadi Carnot discovered the thermodynamic rules for the heat-pumping technologies and he more or less predefined the first and the second laws of thermodynamics which were formulated in 1842 by Robert Mayer and in 1850 by Clausius. Following the energy discussion of today one might suppose that Carnot and Clausius had never existed.

Whether (H)CFCs really deplete the ozone layer is still a question. The consequences of an increased concentration of greenhouse gases like CO_2 and CH_4 in the atmosphere are, at least over a longer time scale, well known from the history of Greenland Ice. Probes of this ice show that an increased CO_2 concentration results in a significant increase of the average temperature on our planet and therefore a climate change. This means that we have to use our fossil fuels carefully, we have to utilize them more efficiently. Heat pumps are one of the key technologies to achieve this goal.

"Success on the market is not a phenomenon, it is the result of research, excellent products, skilled installers, the support of the utilities and a political target"

If we do not forget these preconditions, if governments accept the importance of this technology, if there is a real need for the reduction of CO_2 emissions resulting from international agreements, heat pumps will also succeed in Europe and contribute to a better future. It is high time, considering the Kyoto targets, to spread the knowledge and increase the awareness of heat pumps as an energy-efficient and environmentally benign technology across Europe. However, one goal has not been achieved until now: the goal of convincing politicians.

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Kogeneracija v sodobnih sistemih za ogrevanje, prezračevanje in klimatizacijo

Cogeneration in Modern Systems for Heating, Ventilation, Air-Conditioning and Cooling (HVAC)

Petar Donjerković - Hrvoje Petrić

Sodobni razvoj majhnih kogeneracijskih obratov v zahodnih deželah kaže, da energija in okolju prijazna rešitev nista samo zaželeni, ampak tudi gospodarni. Kogeneracijske izvedbe velikih, srednjih in celo dandanes majhnih ogrevalnih, prezračevalnih in klimatiziranih obratih (OPK - HVAC), postajajo običaj v modernih sistemih.

Prispevek se ukvarja z osnovami kogeneracijskih OPK sistemov, z upoštevanjem batnih strojev v kombinaciji s prenosniki toplote in absorpcijskimi hladilnimi napravami. Opisan sistem je analiziran z vidika osnovne energijske, ekologijske in gospodarstvene povezanosti. Predstavljena je tudi pred kratkim popularna mikro kogeneracija za majhen OPK sistem.

Konstrukcija kogeneracijskih OPK sistemov je pogosto povezana s delnimi problemi ali celo ovirami, ko se primerja z instalacijo običajnega sistema, predstavljeni so tudi nekateri glavni problemi.

Končno so teoretična spoznanja kogeneracijskih OPK sistemov vključena v primer, odkrit v bolnišnici na Hrvaškem. Omenjen sistem v resnici prikazuje glavne tehnične in gospodarstvene značilnosti tega sistema.

Na koncu predstavlja prispevek vodila za sodobni razvoj upravljanja z energijo kot funkcijo moči, ogrevanja in proizvodnje hladilne energije. Razloži, da kogeneracijski OPK sistemi niso primerni samo s tehničnega vidika, ampak tudi z gospodarskega.

(Ključne besede: kogeneracija, sistemi HVAC, gospodarjenje energetsko, analize sistemov)

Present trends in Western countries suggest that small cogeneration plants are preferable not only in terms of energy and the environment but also from the economic perspective. The application of cogeneration in large, medium and nowadays even small heating, ventilation and air-conditioning (HVAC) plants, is becoming common in modern systems.

This paper deals with the basics of cogeneration-HVAC systems, considering reciprocating engines in conjunction with heat exchangers and absorption chillers. The described system is analyzed from the point of view of key energy, ecology and economy correlations. Moreover, an introduction to the recently popular micro-cogeneration for a small HVAC system is given.

Since the construction of cogeneration-HVAC systems can often be linked with practical problems or even barriers, particularly when compared with the installation of a conventional system, some of these major problems are also described.

Finally, these theoretical considerations of cogeneration-HVAC systems are integrated with an example from a hospital in Croatia. This example illustrates the main technical and economic characteristics of such a system on a real site.

As a conclusion, the paper introduces guidelines to modern energy-management trends as a function of power, heating and cooling energy production. It explains that cogeneration-HVAC systems are viable not only from the technical point of view, but also from the economic one.

(Keywords: cogeneration, HVAC systems, energy management, system analysis)

0 UVOD

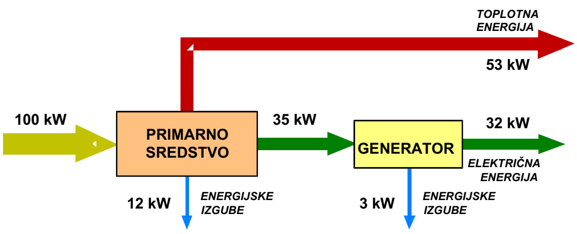
Sodobni razvoj v Zahodnih deželah kaže, da je smotrna uporaba energije z njenimi gospodarskimi in ekološkimi zahtevami osnovna predpostavka vzdržljivega razvoja. Izvedbe različnih modernih tehnologij za

0 INTRODUCTION

Present trends in Western countries show that the rational use of energy, with its economic and ecological hypothesis, is the basic requirement for sustainable development. The application of pridobivanje energije in predelave pogosto vključuje povečanje investicijskih stroškov, toda njihova gospodarstvena zmožnost in okoliška upravičenost, v primerjavi z drugimi procesi energijske proizvodnje, postanejo očitna šele po zadostni časovni uporabi obrata. Glede na razvoj se kot ena od rešitev pri gospodarjenju z energijo pogosto uporabijo kogeneracijski sistemi.

Kogeneracija je definirana kot logična uporaba primarne energije za pridobivanje dveh uporabnih energijskih oblik: toplotne energije in moči. Omenjen energijsko spreminjevalni postopek je zanimiv, ker je bistveno odvisen od izstopne oblike energije, stanja izkoriščenosti, veličine obrata in lastništva. Za pojasnilo, proizvodno uporabna moč energije se lahko uporabi za generiranje elektrike ali moči, medtem ko se lahko toplotna energija uporabi pri tehnoloških procesih, ogrevalnih procesih ali hladilnih procesih. Pridobljena energija, toplotna in delno električna, se lahko uporabi na kraju samem, ali razdeli drugim porabnikom. Velikost kogeneracijskega sistema se lahko spremeni od zelo majhnih obratov s kapaciteto od nekaj kilovatov (kW) do večjih enot z nekaj sto megavatov (MW). Koristno je lahko biti lastnik takšnega obrata, uporabnik končne energije ali samostojni pridobivalec energije.

Kogeneracijski sistemi so pogosto upoštevani zaradi svojega velikega energijskega izkoristka in v povezavi s tem zmanjšane zračne onesnaženosti, ki potuje skozi sistem, koristi ekološko in ekonomsko. Glede na dejstvo, da lahko celotni izkoristek teh obratov doseže 90 odstotkov, je očitno, da so današnji kogeneracijski sistemi najučinkovitejši in so tako ekološko ustrezna rešitev za proizvodnjo toplote in moči. Slika 1 prikazuje shematski diagram običajnega kogeneracijskega sistema s prikazano predpostavko o celotni učinkovitosti okoli 85 odstotkov [1].



Sl. 1. *Shema energijske predelave v kogeneracijskem sistemu*

1 KOGENERACIJA OPK SISTEMOV

1.1 Kogeneracijska enota

Prednosti kogeneracijske proizvodnje energije skupaj z nedavnim tržnim razvojem, delno pri tistih s trgom elektrike, je povzročilo, da se kogeneracijski sistemi pogosto uporabljajo kakor prej v ogrevalnih, prezračevalnih in klimatizacijskih

various modern technologies for energy production and transformation requires investment, but the economic viability and the environmental benefits are clear after a period of the plant's use. In view of these trends, one of the solutions in energy management, cogeneration systems, are very often used.

Cogeneration is defined as the sequential use of primary energy to produce two useful energy forms: thermal energy and power. This energy-transformation process is interesting because it is essentially independent of the output-energy form, disposition of its utilization, plant size and ownership. As an explanation, useful power the produced can be used either to generate electricity or shaft power, while the thermal energy could be used in technological processes, heating processes or cooling processes. The energy produced, thermal and in particular electrical, can either be used at the site or distributed to other consumers. The size of a cogeneration system can vary from very small plants with a capacity of only a few kilowatts to large units with several hundred megawatts. Finally, the owner of such plants can be a utility, energy end-user or an independent power producer.

Cogeneration systems are most frequently considered because of their high energy efficiency combined with a reduction in the emission of air pollutants.As the overall efficiency of these plants can exceed 90 percent, it is clear that cogeneration systems are currently the most effective and therefore ecological solutions for heat and power production. Figure 1 shows a schematic diagram of a typical cogeneration system with an overall efficiency of about 85 percent [1].

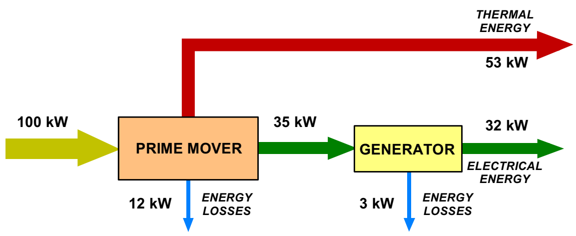


Fig. 1. *Scheme of the energy conversion in a cogeneration system*

1 COGENERATION HVAC SYSTEMS

1.1 The cogeneration unit

The advantages of cogeneration energy production, together with the recent market deregulation trends, particularly those of the electricity market, mean that cogeneration systems are increasingly being used in heating, ventilation sistemih (OPK). Kogeneracijske sisteme poznamo kot velike sisteme s toplotno zmogljivostjo deset in več megavatov (MW), srednje z nekaj sto kilovati (kW) do majhnih sistemov z nekaj deset kW. Na tržišču je nekaj znanih proizvajalcev, ki ponujajo kogeneracijske sisteme kot paketne enote, ki se prilagodijo na energijski sistem objekta.

Običajno si lahko kogeneracijske enote zamislimo z različnimi primarnimi sredstvi, zadnje čase pa najbolj splošno uporabljive, tržno razpoložljive kogeneracije vsebujejo batne stroje z notranjim zgorevanjem, zgorevalne turbine ali parne turbine. Druge tehnologije npr. batni parni stroj, Stirlingov motor ali bencinske celice, se manj uporabljajo ali se še zmeraj v preskušajo in niso tržno uporabljive.

Upoštevajoč kogeneracijske enote v OPK sistemih lahko potrdimo, da se običajno uporabljajo batni stroji z notranjim zgorevanjem. Dokazano je, da so omenjeni stroji cenovno uspešni pri kogeneracijskih izvedbah in z velikim izkustvenim znanjem pri različnih izvedbah in v različnih obratovalnih razmerah. Batni stroji imajo visoko učinkovitost (do 50 odstotkov), celo v manjših velikostih, z dobro storitvijo pri polovični obremenitvi, kratkim zagonom do polne obremenitve in s primerno majhnim vgradnim prostorom. Poleg tega so razpoložljivi v velikem številu različnih velikosti, v nizu od deset kW do nekaj megavatov (MW). S tipično razpoložljivostjo od 7600 do 8400 ur na leto, so najbolj primerni pri izvedbah do dveh ali treh megavattov (MW) [2].

Glede na termodinamični proces in gorivo, se batni stroji delijo v dve osnovni skupini: bencinske in dizelske motorje. Bencinski motorji so znani kot plinski motorji, ki delujejo popolnoma na plin (naravni plin, LPG, bioplin, zemeljski plin itn.), medtem ko diselski motorji uporabljajo tekoče gorivo ali dvojno mešanico goriva (mešanica naravnega plina z majhnim deležem tekočega goriva). Za majhne zmogljivosti se ponavadi uporabljajo spontani sesalni motorji, medtem ko se za največje moči uporabljajo stroji z dodatnim polnjenjem.

Omenjeni stroji lahko dajejo toplotno energijo v obliki vroče ali vrele vode do 120 °C, in/ali pare nizkega tlaka (do 5 bar) z uporabo odpadne toplote izpušnih plinov (približno 1/3 koristne toplote) v plinskem prenosniku in hladilni vodi (približno 2/3 koristne toplote). Horizontalni ali vertikalni oklepni in cevni prenosniki toplote (voda – voda, voda – mazno olje in voda – para) se uporabljajo za pridobivanje odpadne toplote. Parni generatorji (PG) za pridobivanje toplote vsebujejo tudi cevne prenosnike toplote, ki se uporabljajo za prenos odpadne toplote izpušnih plinov v paro in/ali vodo. Slika 2 prikazuje načelno shemo kogeneracije z uporabo sesalnega in dodatno polnjenega batnega stroja, strnjen s poenostavljenim energijskim pregledom.

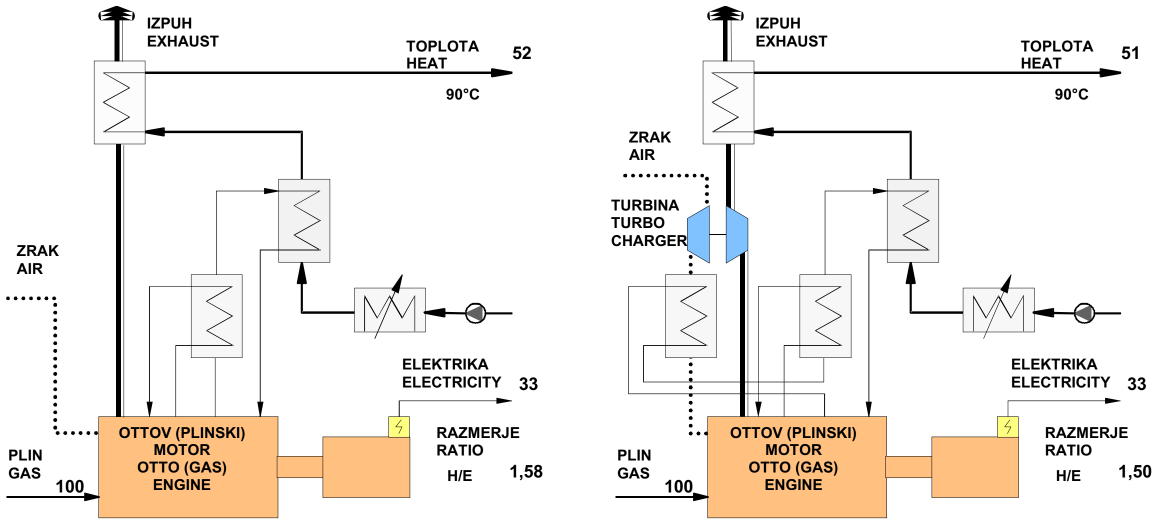
and air-conditioning systems (HVAC). Cogeneration systems range from large systems with a heat capacity of ten or more megawatts, to medium-size units with a few hundred kilowatts, to small systems with a few tens of kilowatts. There are a large number of well-known producers in the market that offer cogeneration systems as packaged units which are tailored to the building energy systems.

Cogeneration units can make use of various prime movers, but recently the most commonly employed commercially available cogenerations include internal combustion reciprocating engines, combustion turbines or steam turbines. Other technologies, like reciprocating steam engines, Stirling engines or fuel cells are less frequently used or remain in the demonstration stage and not in commercial operation.

For cogeneration units in HVAC systems internal combustion reciprocating engines are usually used. These engines have proven to be cost effective in cogeneration applications, and there is considerable operational experience for very different applications and under different operating conditions. Reciprocating engines are characterized by high efficiency (up to 50 percent), even for the smaller sizes, good performance at partial loads, short startup to full load and a comparatively small installation space. They are available in a large wide range of different sizes, ranging from tens of kilowatts to a few megawatts. With typical availabilities of 7600 to 8400 hours per year, they are most sutable for applications requiring up to two or three megawatts [2].

With respect to the thermodynamic cycle and the fuel, reciprocating engines fall into two basic groups: Otto engines and Diesel engines. Otto engines are often known as gas engines since they regularly operate on gas (natural gas, LPG, biogas, landfill gas, etc.), while Diesel engines use liquid fuel or a dual fuel mix (mixture of natural gas with a small portion of liquid fuel). For the smaller capacities they are usually naturally aspired (atmospheric) engines, while the biggest sizes are supercharged or turbocharged engines.

These engines can produce thermal power in the form of hot or warm water up to 120°C, and/or low pressure steam (up to 5 bar) using the rejected heat of the exhaust gases (about 1/3 of the available heat) in the gas exchanger and cooling water (about 2/3 of the available heat). The horizontal or vertical shell and tube heat exchangers (water-water, water-lube oil and water-steam) are used for waste-heat recovery. The heat-recovery steam generators (HRSGs) also include tube heat exchangers used for the transmission of the rejected heat of exhaust gases to steam and/or water. Figure 2 shows the principle of cogeneration using atmospheric and turbocharged reciprocating engines, integrated with a simplified energy balance.



Sl. 2. *Kogeneracijska enota s sesalnim in dodatno polnjenim batnim strojem*

Fig. 2. *Cogeneration unit with atmospheric and turbocharged reciprocating engine*

Visok celotni energijski izkoristek teh sistemov je lahko zapisan (med 78 in 88 %, glede na razpored) in izgube so zaradi izgub v dimniku (8 do 10 %, plini okoli 120 °C), sevanja iz stroja (3 do 5 %) in izgube zaradi trenja na gredi stroja – generatorja (1 do 2 %) [3].

1.2 Absorpcijske hladilne naprave

Ključni parameter za kogeneracijski izbor je podan s toplotno in energijsko porabo, ker je kogeneracija najučinkovitejša, ko pokriva osnovne obremenitve. Pomembno je, da so osnovne toplotne in energijske obremenitve pomemben delež v celotni letni energijski porabi in bi morale omenjene obremenitve trajati več ko 3000 do 6000 ur na leto, nakar kogeneracija postane sprejemljiva. Zato je namen, da s kogeneracijo zagotovimo hladilno energijo v OPK sistemu. Proizvodnja hladilne energije v kogeneracijskih sistemih je zasnovana na izvedbah absorpcijskih hladilnih naprav, ki uporabljajo toplotno energijo iz sistema.

Proizvodnja hladilne energije v kogeneracijskih sistemih je najpogosteje utemeljena na izvedbah absorpcijskih hladilnih naprav, ki uporabljajo toplotno energijo iz sistema, obstajajo celo raztopine, pri katerih uporabljajo mehanske stiskalne naprave. Odkar je prva različica običajna, je kratek pregled tehnologije opisan v nadaljevanju.

Slika 3 prikazuje preprost shematski diagram in primerjavo absorpcijskih in kompresijskih hladilnih krogov. Nekateri avtorji so v absorpcijskem krogu označili s črtkano črto termični kompresor, da bi prikazali podobnost z mehaničnim kompresorjem v kompresorskem krogu [4].

Razlika med absorpcijskim in kompresijskim krogom leži v obliki krožnega nastajanja visokega tlaka pare (VT) od sedanjega nizkega tlaka (NT).

These systems have a high overall energy efficiency between 78 and 88% (according to the arrangement). Losses occur in the stack (8 to 10%, gases at around 120°C), radiation from the engine (3 to 5%) and losses resulting from friction in the engine-generator shaft (1 to 2%) [3].

1.2 Absorption chiller

The key parameter for cogeneration selection is the characteristics of the heat and power consumption as cogeneration is most effective when covering basic loads. It is important that basic heat and power loads represent a significant part of the total annual energy consumption and that these basic loads should exist for more than 3000 to 6000 hours per year since at this point cogeneration becomes viable. Therefore, the intention is to ensure cooling energy in the HVAC system by cogeneration.

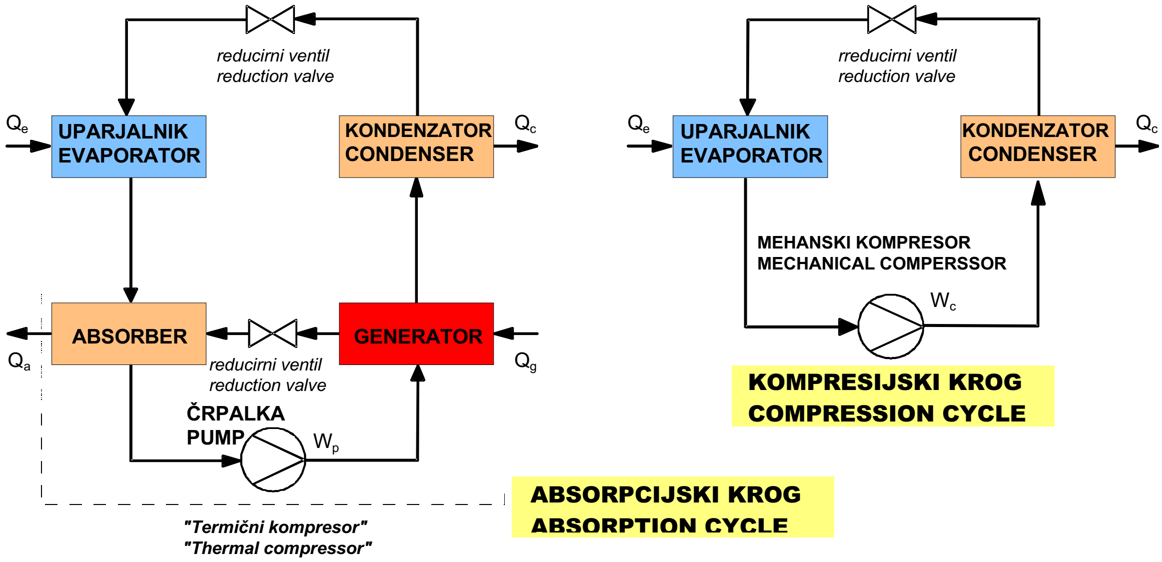
The production of cooling energy in cogeneration systems is most frequently based on the application of absorption chillers that use thermal energy from the system, even when mechanical compression devices are used, solutions also exist. Since the first variant is common, a brief overview of this technology is provided.

Figure 3 shows a simple schematic diagram and comparison of the absorption and compression cooling cycles. Some authors refer to the part of the cycle marked by dotted lines as the “thermal compressor” in order to point out the similarity with the mechanical compressor in a compression cycle [4].

The difference between the absorption and the compression cycle lies in the form of the cyclical generation of high-pressure (HP) steam from the present lowpressure (LP). The mechanical

Mehanski kompresorji omogočajo neposredno stiskanje pare, medtem ko je termično stiskanje sestavljeno iz treh stopenj:
(1) sprememba pare NT v kapljevino VT;
(2) sprememba kapljevine NT v kapljevino VT;
(3) sprememba kapljevine VT v paro VT.

compressor makes direct steam compression possible, while thermal compression consists of three stages:
(1) transformation of LP steam to LP liquid;
(2) transformation of LP liquid to HP liquid;
(3) transformation of HP liquid to HP steam.



Sl. 3. *Primerjava med absorpcijskimi in kompresijskimi krogi*
Fig. 3. *Comparison between absorption and compression cycles*

Druga in tretja stopnja sta izvedeni s preprosto črpalko in generatorjem (vrelnik), medtem ko je prva stopnja izvedena v absorberju, ki daje ime procesu. V absorberju se mrzla para NT, ki prihaja iz uparjalnika, absorbira v revno raztopino, vrnjeno iz generatorja zaradi nizke temperature pare. Črpalka ustvari bogato raztopino (tekočino) pri tlaku generatorja, kjer se ponovno uparja.

Energijska bilanca absorpcijskega kroga je prikazana z naslednjo enačbo:

The second and the third stages are carried out by a simple pump and a generator (boiler), while the first stage is performed in an absorber which gives the process its name. In the absorber the cold LP steam that comes from the evaporator is absorbed into the poor solution returned from the generator due to the lower steam temperature. The created rich solution (liquid) is pressed by the pump at the generator pressure level where it evaporates again.

The energy balance of the absorption cycle is shown by the following equation:

$$Q_g + Q_e + W_p = Q_c + Q_a \quad (1)$$

Pomen simbolov: Q_g - toplota, ki vstopa v generator, Q_e - toplota, ki vstopa v uparjalnik, W_p - energija, ki jo porabi črpalka (zanemarljivo), Q_c - izločena toplota iz kondenzatorja in Q_a - izločena toplota iz absorberja.

Teoretični absorpcijski krog z idealnim hladivom in absorberjem ter konstantno latentno toploto, je odvisen od tlaka P in temperature T, ta bi imel vrednost HŠ[1] blizu 1. V praksi, komercialne naprave delujejo z vrednostjo HŠ okoli 0,6 do 0,7 [5].

Najboljša storitev v omenjenem krogu je dosežena z uporabo toplote, pridobljene v kondenzatorju z dodatno ločitvijo hladiva v

Where: Q_g is the heat entering the generator, Q_e is the heat entering the evaporator, W_p is the energy consumed by the pump (neglected), Q_c is the heat extracted from the condenser and Q_a is the heat extracted from the absorber.

The theoretical absorption cycle, with ideal absorbent and refrigerant and a constant latent heat independent of P and T, would have a COP[1] value close to 1. In practice, commercial equipment operates with a COP value of about 0.6 to 0.7 [5].

The best performance in this cycle is achieved by using the heat obtained in the condenser for the additional separation of the refrigerant into

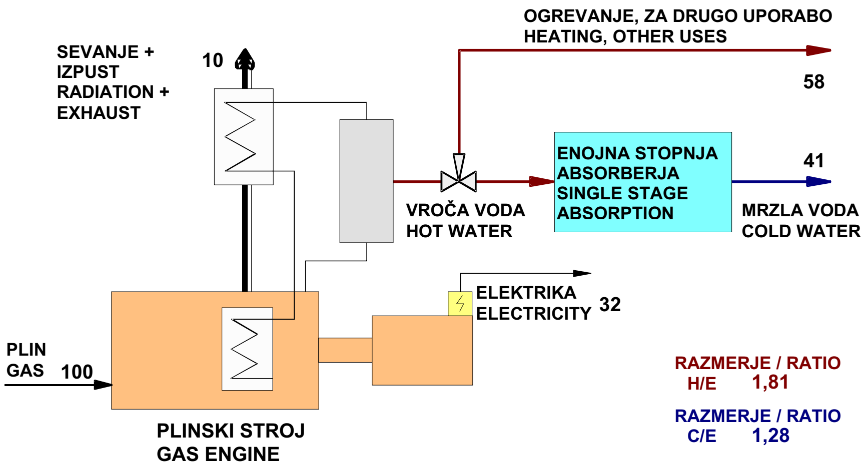
[1] HŠ – Hladilno število: Razmerje med energijo (hladno ali toplo), generirano s ciklom (kompresija ali absorpcija), glede na uporabljeno energijo v kompresorju ali generatorju.
[1] COP – Coefficient of Performance: The relation between the energy (cold or heat) generated by the cycle (compression or absorption) with respect to energy applied to it in the compressor or generator.

kondenzatorju (nizko temperaturni generator). V podobnem dvostopenjskem absorpcijskem krogu z enako vstopno toploto, se tok hladiva v uparjalniku poveča in v teoretičnem primeru je vrednost HŠ[1] skoraj 2. V praksi delujejo tržne dvostopenjske absorpcijske hladilne naprave z vrednostjo HŠ med 1,3 in 1,3 [5].

Absorpcijske hladilne naprave uporabljajo hladivo/absorbent v dvojici bodisi amonijak/vodo (NH_3/H_2O) ali vodo/litijev-bromid (H_2O/LiBr) raztopino, s skoraj enakim termodinamičnim izkoristkom, ki je odvisen od zmogljivosti in delovnih temperaturnih razmer. Najnižje hladilne temperature, ki se lahko dosežejo z absorpcijskimi hladilnimi napravami, so v območju od +4 °C do +6 °C. Zaradi delovanja kot vstopno sredstvo, enostopenjski sistemi potrebujejo bodisi vročo/toplo vodo (90 do 110 °C) ali nizkotlačno paro, medtem ko dvostopenjske enote uporabljajo paro višjega tlaka. Glede na zapisano se enostopenjske absorpcijske hladilne naprave običajno uporabljajo v manjših in srednjih kogeneracijskih OPK sistemih, medtem ko večje enote s proizvodnjo pare uporabljajo dvostopenjske enote. Slika 4 prikazuje shemo kogeneracijskega obrata z absorpcijsko hladilno napravo kot del OPK sistema. Ker opisan sistem pridobiva tri različne oblike energije, in sicer moč, toploto in hladilno energijo, je običajno identificiran kot trigeneracijski sistem.

condenser (low-temperature generator). In such a two-stage absorption cycle, with the same input heat, the flow of refrigerant in the evaporator is increased, and for the theoretical case the COP value is almost 2. In practice, commercial two-stage absorption chillers operate with a COP value between 1.2 and 1.3 [5].

Absorption chillers use either ammonia/water (NH_3/H_2O) or water/lithium-bromide (H_2O/LiBr) solutions as the refrigerant/absorbant pair with an almost equal thermodynamic efficiency, the choice depending on the capacity and operating temperature. The lowest cooling temperatures that can be reached with absorption chillers are in the range from +4 to +6°C. For the input medium, single-stage systems require either hot/warm water (90 to 110°C) or low-pressure steam, while two-stage units use higher pressure steam. As a consequence single-stage absorption chillers are commonly used in small and medium-size cogeneration-HVAC systems, while larger units with steam production use two-stage units. Figure 4 shows a scheme for a cogeneration plant with an absorption chiller as a part of the HVAC system. Since a system like this produces three different forms of energy, that is power, heat and cooling energy, it is usually recognized as a trigeneration system.



Sl. 4. *Trigeneracijska shema za OPK sistem*

Fig. 4. *Scheme of trigeneration for HVAC system*

1.3 Mikro-kogeneracija

Zgoraj opisani kogeneracijski sistemi se uporabljajo dandanes v srednjih in velikih OPK sistemih, kar pomeni, da običajno delujejo z najmanjšo razpoložljivo termično kapaciteto približno 100 kW_t s 50 kW_e moči. Manjši sistemi od teh, ki bi se lahko uporabili v družinskih hišah ali nekaj podobnega, še vedno niso v tržni rabi.

Vseeno mora biti omenjeno, da so nedavno napredovanje in usmeritve energijskega tržišča v

1.3 Micro-cogeneration

The above-described cogeneration systems are currently used in medium and large HVAC systems, which means they usually operate with the smallest available thermal capacity of about 110 kW_t with 50kW_e of power. Smaller systems than these, which could be used in family houses, are not yet in commercial production.

Recent progress and the deregulation of energy markets in Europe are motivating the

Evropi spodbudile razvoj mikrokogeneracije, ki je namenjena za družinsko uporabo, zagotavljajoč termični izstop od 10 do 25 kW_t in električni izstop, manjši odt 10 kW_e. Podobne mikrokogeneracije temeljijo na Stirlingovem motorju, bencinskih celicah ali majhnih plinskih motorjih. Kot gorivo uporabljajo naravni plin ali utekočinjene naftne pline in celotni primarni energijski izkoristek do 95 odstotkov z majhno NO_x, CO in ogljikovodikovo oddajo. Primerjava z običajnimi plinsko centralno ogrevanimi kotli za gospodinjske objekte, kjer se 80 do 90 odstotkov primarne energije (naravni plin) preoblikuje v uporabno toploto, prav tako je jasno, če upoštevamo ceno elektrike za gospodinjstva, da imajo takšni sistemi dobro prihodnost.

Odslej potrebne tehnologije obstajajo in glavno vprašanje je, kako doseči ravnovesje med delovnimi urami in shranjeno/toplotno izgubo, prav tako kakor število enot začetka/konca. Še vedno primanjkuje informacij o zanesljivosti in učinkovitosti Stirlingovega motorja, prilagodljivosti plinskih motorjev in dobi trajanja bencinskih celic. Na splošno je priznano, da bodo omenjena vprašanja in nepoznana dejstva, dokazana v naslednjih dveh ali treh letih, tudi izpolnitev specifičnih tehnologij bo prav tako dokazana. Domneva se, da lahko pričakujemo prvi tržni sistem podobne vrste že v petih letih [6], tržno uporabo pa kasneje. Vsekakor bo omenjeno neposredno povezano s procesom razvoja in sprostitve energijskega tržišča.

development of micro-cogeneration that is intended for household applications, providing a thermal output of 10 – 25 kW_t and an electric output of less than 10 kW_e. Such micro-cogenerations are based on Stirling engines, fuel cells or small gas engines. As a fuel they use natural gas or LPG (Liqueid Petroleum Gases), and offer overall primary energy utilization up to 95 percent with low NO_x, CO and hydrocarbon emissions. In comparison with conventional gas central-heating boilers for households where 80 – 90 percent of primary energy (natural gas) is transformed to useful heat, and taking into account the price of electricity for households, it is clear that such systems have a promising future.

So the required technologies exist and the main issue is how to reach a balance between running hours and storage/heat losses, as well as the number of unit starts/stops. There is also still a lack of information on reliability and efficiency of Stirling engines, the flexibility of gas engines and the timescale for fuel cells. It is generally accepted that these problems and unknowns will become established within the next two or three years, although the specific technology to be implemented will also have to be proven. It is expected that the first commercial system of this kind can be expected in five years [6], although real commercial exploitation will arrive later. Progress will be directly connected to the development process and deregulation of the energy market.

2 RAZVOJ OGRODJA ZA KOGENERACIJSKI OPK SISTEM

2 THE FRAMEWORK FOR COGENERATION-HVAC SYSTEMS DEVELOPMENT

2.1 Tržne prednosti

Zgornji opis ponazarja tehnične zmožnosti kogeneracije in trigeneracije OPK sistemov, toda končno uvajanje takšnega sistema ima edino pomen, če ga je mogoče uskladiti s tržnimi možnosti. Koristnost kogeneracijskih sistemov je vnaprej odvisna od (1) razlike med odpravno ceno elektrike in ceno goriva, (2) števila obratovalnih ur sistema in (3) potrebne investicije.

Na podlagi poenostavljenega ekonomičnega modela, kjer predstavljamo, da je cena proizvedene toplote enaka kakor pri običajnih sistemih, tako da je cena pridobljene elektrike preračunana s to vrednostjo in lahko preprosto prikažemo investicijsko odplačilno dobo, in sicer:

2.1 Economic benefits

The above description illustrates the technical viability of cogeneration and trigeneration HVAC systems, but the final adoption of such systems will only make sense if it is accompanied by economic feasibility. The profitability of cogeneration systems primarily depends on (1) the difference between the avoided electricity cost and the fuel cost; (2) the number of system operation hours and (3) required investment.

Based on a simplified economic model that assumes that the price of the produced heat is equal to a conventional system so that the cost of generated electricity is calculated with this value, the simple payback period of investment can be calculated as the follows:

$$PB = \frac{INV}{H \cdot SV} \qquad (2),$$

kjer pomenijo: *INV* - totalni znesek potrebne investicije ($), *H* - letno obdobje obratovanja naprave (h), *SV* - odpravno ceno ure obratovanja ($/h). Slednje se lahko izračuna kot:

Where *INV* is the required investments ($), *H* is the annual plant operation period (h) and *SV* represents the avoided costs per hour of operation ($/h). *SV* can be calculated as:

$$SV = EP \cdot \left(Ea - \left[\frac{F - Fa \cdot \frac{\eta_t}{\eta_{ref}}}{\eta_e} \right] - MC \right) \qquad (3),$$

kjer so: *EP* - električna moč obrata (kW_e), *Ea* - povprečna električno odpravna cena ($/kWh$_e$), *F* - cena goriva za kogeneracijo ($/kWh$_e$), *Fa* - odpravna cena goriva ($/kWh$_e$), *MC* - cena vzdrževanja kogeneracije ($/kWh$_e$), *$* - upoštevana valuta za investicijo, η_t - toplotni izkoristek kogeneracije, η_{ref} - toplotni izkoristek kotla in η_e - električni izkoristek kogeneracije.

Investicijski stroški vštetih sistemov vsebujejo stroške samega kogeneracijskega obrata, električne opreme, prilagoditev sedanjega OPK sistema, hladilni stroj in ventilator ter druge instalacijske stroške. Cena samega kogeneracijske naprave je v obsegu od 400 do 700 USD/kW_e za majhne enote, do 300 do 400 USD/kW_e za večje enote. Totalni investicijski stroški celotnega sistema (brez absorpcijske hladilne naprave) so v obsegu od 1100 do 1800 USD/kW_e za manjše enote, do 550 do 700 USD/kW_e za večje enote [7].

Če je sistem konstruiran kot trigeneracijski, kar pomeni z absorpcijsko hladilno napravo, se investicijski stroški povečajo v območju od 200 do 300 USD/kW_e za majhne enote in za večje enote približno do 100 USD/kW_e [7].

Navedene številke so le primer, da bi ovrednotili projekt, je za vsako lokacijo potrebno proučiti njegovo primernost na osnovi zapletenih ekonomskih modelov, trenutnih cen in stroškov. Izkušnje evropskih držav nakazujejo, da je verjetni odplačilni čas za srednje in večje kogeneracijske in trigeneracijske OPK sisteme okoli štiri do sedem let [7]. Razumljivo, da je vse omenjeno odvisno od številnih dejavnikov, pravnih ureditev in zakonodaje, prav tako od goriva in električne tarife v obravnavani državi.

2.2 Kogeneracijske ovire

Čeprav je kogeneracija je odobrena s tehničnega (energija) vidika, skupaj z očividnimi okoliškimi in tržnimi prednostmi, pa se pogosto zgodi, da kogeneracija ni dobro prepoznavna ali definirana v pravni obliki in v predpisih posamezne države. Najbolj pogoste kogeneracijske ovire, ki so bile lahko odkrite, so:

- ni primernega zakona za prodajo in nakup električnega presežka kogeneracijskega obrata ali nezadovoljive (nespodbudne) tarife, razen običajnih visokih tarif za vršne moči (za stanje pripravljenosti in podpiranja) iz energijskega sistema;
- nezadovoljive tarife naravnega plina in drugih goriv za kogeneracijske obrate;
- dolgi in birokratski postopki za pridobitev potrebnih dovoljenj in pogosto administrativnih ovir;
- omejitve glede razpoložljivega povezanja in uporabo distribucijskega omrežja za generirano elektriko;

Where *EP* is the electrical power of the plant (kW_e), *Ea* is the average avoided electricity cost ($/kWh$_e$), *F* is the cost of the fuel for cogeneration ($/kWh$_e$), *Fa* is the avoided fuel cost ($/kWh$_e$), *MC* is the cost of cogeneration maintenance ($/kWh$_e$), *$* is considered the currency for investment, η_t is the thermal performance of cogeneration, η_{ref} is the thermal performance of the referent boiler and η_e is the electrical performance of cogeneration.

The investment costs of the considered systems include the cost of the cogeneration plant, electrical equipment, adaptation of the existing HVAC system, engine cooling and ventilation and other installation costs. The price of the cogeneration plant ranges from 400 to 700 USD/kW_e for small units, to 300 to 400 USD/kW_e for large units. The total investment costs for a complete system (without absorption chiller) range from 1100 to 1800 USD/kW_e for smaller systems, to 550 to 700 USD/kW_e for large systems [7].

If the system is designed for trigeneration, which means it includes an absorption chiller, investment costs are increased by 200 to 300 USD/kW_e for small units, to about 100 USD/kW_e for bigger units [7].

These figures are only given as a reference, a feasibility study is required to validate the project for each location with complex economic models and actual prices and costs. The experience of European countries shows that the probable payback period for medium and large cogeneration and trigeneration HVAC systems is about four to seven years [7]. Obviously this depends on several factors, particularly the regulation and legislation framework, as well as fuel and electricity tariffs in the respective countries.

2.2 Barriers to cogeneration

Even if cogeneration is accepted from the technical (energy) point of view, together with its evident environmental and economic advantages, it is often the case that the position of cogeneration is not clearly recognized or defined in the legal framework and regulations of an individual country. The most common barriers to cogeneration are as follows:

- No appropriate law for buying and selling surplus electricity from cogeneration plants or unsatisfactory (non-stimulating) tariffs. In addition to typically high tariffs for stand-by and back-up peak power from a power system;
- Unsatisfactory tariffs for natural gas and other fuels for cogeneration plants;
- Long and bureaucratic procedures for the procurement of necessar authorizations and administrative barriers;
- Rules regarding connection availability and the use of the distribution network for generated electricity;

– dolg odplačilni čas zaradi neprimerne tržne in pravne oblike;

Skupaj z razvojem energijskega trga in z ureditvijo v evropskih državah, je mnogo omenjenih ovir znižanih ali popolnoma odstranjenih. Vendar, odkar je izvedba kogeneracijskega in trigeneracijskega OPK sistema povezana s povečanimi investicijskimi stroški v primeri z običajnimi sistemi, je treba analizirati vsak projekt preden je izveden. Na tej stopnji je prav tako zelo pomembno ugotoviti, ali zakon obsega vse ključne točke, ki se nanašajo na kogeneracijo in druga vprašanja ali pa se je treba o njih pogajati, da bi se izognili vsem problemom.

– Long payback period due to an inadequate economic and legal framework.

In combination with energy-market development and deregulation in European countries, many of these obstacles are being reduced or completely removed. However, since the implementation of a cogeneration- or trigeneration-HVAC system is linked with increased investments in relation to conventional systems and viability depends on several different issues, it is necessary to analyze each project before its realization. At this stage it is also very important to find out if the law covers all the points relating to cogeneration and other subjects or if it is necessary to negotiate them, to prevent any problems.

3 PRIMER OPK SISTEMA V BOLNIŠNICI

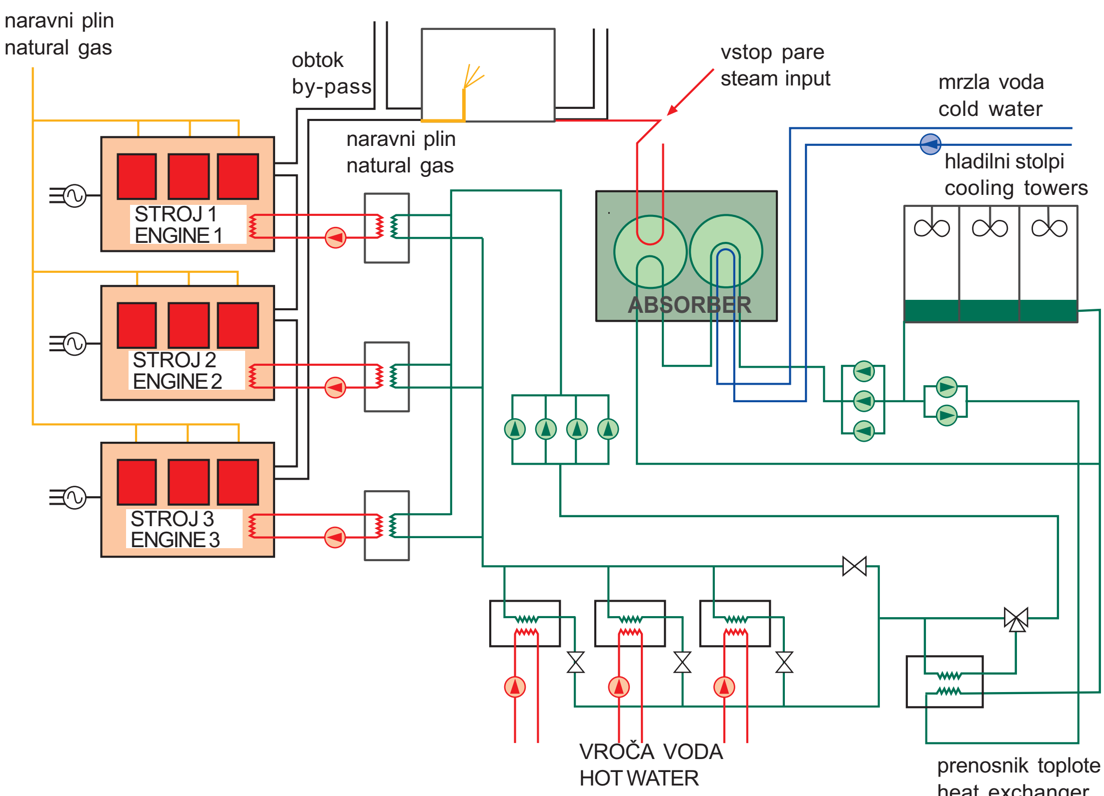
Z željo, da bi povezali zgornja razmišljanja z dejanskim stanjem, bomo predstavili analizo primernosti za trigeneracijski sistem v hrvaški bolnišnici. Bolnišnica je v mestu Zagreb z značilnostmi celinskega podnebja. Bolnišnica je sodoben objekt, končan leta 1988, z načrtovano velikostjo 755 ležišč in kasneje skrčeno približno na 500 ležišč.

Energijske potrebe bolišnice so tipične za takšne objekte: (a) primarna: elektrika, hišna vroča voda, ogrevanje (pozimi) in hlajenje (poleti); ter (b) sekundarna: pranje, sterilizacija in sežiganje.

3 EXAMPLE OF A HVAC SYSTEM IN A HOSPITAL

To link the above considerations to a real situation we will present an example of a feasibility analysis for a trigeneration system in a hospital in Croatia. The hospital is located in Zagreb with a continental-type climate. The hospital is a modern building finished in 1988, with a projected size of 755 beds later reduced to about 500 beds.

The energy needs of the hospital are typical for such an institution: (a) primary - electricity, domestic hot water, heating (winter), and cooling (summer); and (b) secondary – laundry,



Sl. 5. *Shema novega sistema*
Fig. 5. *Scheme of new system*

Sedanji OPK sistem vključuje enostopenjsko absorpcijsko hladilno napravo, ki deluje na paro iz sedanjih kotlov.

Glede na dejstvo, da bolnišnica deluje vse leto, tudi energetski sistem deluje nepretrgano celo leto. Analizirane so možnosti uvedbe kogeneracijskega postrojenja,ki bi pokrilo vse ali del potreb po energiji.

Celotna letna poraba elektrike znaša približno 15,5 GWh s pogodbeno močjo 2200 kW. Celotna proizvodnja pare znaša približno 73 000 ton na leto, od tega so potrebe za ogrevanje in hlajenje (absorber) približno 59 000 ton. Celotna letna poraba naravnega plina znaša 5 000 000 m^3, od tega porabi ogrevanje in hlajenje skoraj 4 750 000 m^3.

Parni proizvodni obrat je sestavljen iz treh kotlov z vgrajeno zmogljivostjo 3 x 6 000 kW, tlaka 10 bar in zmogljivostjo okoli 9 ton/h pri 185 °C. Za proizvodnjo hladilne energije se uporabljata enostopenjska absorpcijska hladilnika z vgrajeno zmogljivostjo 2 x 2700 kW (0,8 bar). Para se uporabi pri toplovodnih ogrevalnih sistemih (110/70 °C) skozi štiri prenosnike toplote z zmogljivostjo 4 x 800 kW.

Analizirana je vgradnja kogeneracijskega obrata, ki bi deloval neprestano vse leto. Tehnična zamisel projekta vključuje vstavitev enega ali več plinskih (Ottovih) batnih strojev, ki lahko pridobivajo elektriko, vročo vodo in nizko tlačno paro. Slika 5 prikazuje shemo predlaganega sistema.

Analizirane so tri različne izbire: (A) vgradnja enega stroja z zmogljivostjo 3,8 MW_e, (B) vgradnja dveh strojev z zmogljivostjo 2 x 2,9 MW_e in (C) vgradnja treh strojev z zmogljivostjo 3 x 1,0 MW_e. Izbor se spreminja samo z velikostjo obrata, torej različno porabo goriva v kogeneraciji in največjo obremenitvijo kotlov (sedanjih), prav tako je različna proizvodnja elektrike, ki se uporabi na lokaciji, ali se proda javnim uporabnikom. Omenjene vrednosti niso prikazane spodaj, so pa vključene v izračun. Osnovna predpostavka preračunavanja je, da je električni presežek lahko prodan javnim porabnikom za ceno 85 % povprečne električne cene (5,5 USc/kWh), naravni plin je po 13,5 USc/m^3 in cena pogodbene rezervne moči na višini 50%. Finančni stroški so preračunani na podlagi predpostavke investicijskih financ pri 30/70-odstotni stopnji (lastni kapital/kredit), s 15-odstotnim deležnim razmerjem in s 5-letnim odplačilnim obdobjem.

Preglednica 1 podaja rezultate analize, ki temeljijo na teh predpostavkah. Zaradi občutljivosti projekta preglednica 2 podaja analizo podobnih primerov s spremenjenimi cenami naravnega plina in električnimi tarifami.

Omenjeni rezultati prav tako kakor prejšnji zaključki prikazujejo, da pri analiziranem primeru ni tehničnih problemov pri kogeneracijski izvedbi. Končni odgovor in odločitev sta odvisna samo od

sterilization and hospital-waste incineration. The existing HVAC system includes a single-stage absorption chiller operated by steam from existing boilers.

As the hospital works during the whole year, the energy system also runs continuously during year. The possibility of introducing a cogeneration plant that would cover all or part of the energy demands is analyzed.

The total annual electricity consumption is about 15.5 GWh with contracted power of 2200 kW. Total steam production is about 73 000 t per year, the requirements for heating and cooling (absorber) are about 59 000 t. Total annual natural gas consumption is about 5 000 000 m^3 of which heating and cooling consume almost 4 750 000 m^3.

The steam production plant consists of three boilers with a capacity of 3 x 6 000 kW, pressure 10 bar and production capacity of about 9 t/h at 185°C. For cooling-energy production, two single-stage absorption chillers are used with an installed capacity of 2 x 2 700 kW (0.8 bar). The steam is used in a warm-water heating system (110/70°C) through four heat exchangers with a capacity of 4 x 800 kW.

The installation of a cogeneration plant that would run continuously over a year is analyzed. The technical concept of the project includes the embedding of one or more gas (Otto) reciprocating engines that would generate electricity, hot water and low-pressure steam. Figure 5 shows a scheme of the proposed system.

To find the optimum economic viability, three different options are analyzed: (A) installation of one engine with a capacity of 3.8 MW_e; (B) installation of two engines with capacity 2 x 2.9 MW_e and (C) installation of three engines with capacity 3 x 1.0 MW_e. The options only vary in terms of plant size, and consequently the different fuel consumption of cogeneration and peak boilers (the existing ones), as well as the different electricity production that is used in a location or sold to the public grid. These values are not shown below, but are included in the calculations. The basic assumption of the evaluation is that the electricity surplus can be sold to the public grid for 85% of the average electricity price (5.5 USc/kWh), natural gas 13.5 USc/m^3 and contracted back-up power cost at the 50% level. The costs are calculated assuming investment finance at the 30/70 percent level (own funds/ credit), with a 15% interest rate and a 5-year payment period.

Table 1 gives the analysis results based on these assumptions. Due to the estimation of project sensibility, table 2 gives analysis of the same cases with altered prices of natural gas and electricity tariffs.

These results, as well as the previous conclusions show that no technical difficulties for cogeneration implementation in the analyzed hospital are present. The final answer and decision depends only on the circumstances of fuel supply and

Preglednica 1. *Vpeljivost kogeneracije v bolnišnici*
Table 1. *Cogeneration viability in hospital*

	Primer (A) Option (A)	**Primer (B) Option (B)**	**Primer (C) Option (C)**
celotna investicija v USD overall investment in USD	2 550 000	3 900 000	2 400 000
odplaèilni èas payback period	3,0	3,0	2,6
odplaèilni èas (finanèni) payback period (financial)	3,5	3,6	3,3
I.R.R. v % (10 let, finanèno) I.R.R. in % (10 years, financial)	27	27	30

Preglednica 2. *Občutljivost projekta pri spremembi vstopne cene*
Table 2. *Project sensibility at input price change*

Odplaèilni èas Payback period	**Primer (A) Option (A)**	**Primer (B) Option (B)**	**Primer (C) Option (C)**
naravni plin: 23,2 USc/m^3 natural gas: 23.2 USc/m^3	9,0	8,7	5,9
prodajni elektrièni prese□ek: 4,5 USc/kWh selling electricity surplus: 4.5 USc/kWh	5,6	6,0	4,3

nabave goriva in električne tarife, ki imata velik vpliv na izvedbo projekta.

4 SKLEP

Kogeneracijski sistemi ali njihove uporabe se v velikih in srednjih OPK sistemih lahko štejejo kot upravičena tehnologija za proizvodnjo toplote in moči. Sistemi so delno koristni, ko se uporabljajo za hlajenje z absorpcijskimi hladilniki, kar je prepoznavno kot trigeneracija. V takšnih primerih neprestano delovanje vse leto doseže največjo izkoriščenost energije, gospodarske in okoliške prednosti trigeneracijskega (ali kogeneracijskega) sistema.

Izkušnje prikazujejo, da so najprimernejša primarna sredstva za OPK sisteme batni stroji z notranjim zgorevanjem. Omenjeni kogeneracijski sistemi imajo zelo velik izkoristek uporabe primarnega goriva, celo čez 85 odstotkov, zaradi dajanja toplotne energije, ki je primerna za uporabo v OPK sistemu. Prav tako je proizvedena toplota primerna za pogon absorpcijskih hladilnikov, hladilne značilnosti so ponovno izbrane za OPK sisteme. Vzporedna zvezna proizvodnja elektrike lahko zajamči potrebno moč za delovanje vseh naprav znotraj OPK sistema in s časom se lahko uporabi presežek na kraju samem ali pošlje javnim uporabnikom.

Zaradi velike učinkovitosti uporabe goriva in običajne uporabe naravnega plina ali nekatera druga okolju koristna goriva, imajo kogeneracijski obrati majhno oddajo CO_2, SO_2 in NO_x, tako ti sistemi znatno prispevajo k varstvu okolja. Z upoštevanjem teh dejstev, prav tako pa stalne potrebe po gradnji novih energijskih obratov in toplotnih enot, kakor tudi zaradi vedno bolj strogih predpisov na področju

electricity tariffs that have a significant influence on the project feasibility.

4 CONCLUSION

Cogeneration systems, or better their application in large and medium HVAC systems, can be seriously considered as a justified technology for heat and power production. These systems are particularly advantageous when they are used for cooling by the absorption chillers, which is then recognized as trigeneration. In such cases, continuous operation during a whole year is obtained with the maximum utilization of energy.

Experience shows that the most appropriate prime movers for HVAC systems are internal combustion reciprocating engines. Such cogeneration systems have a very high efficiency of primary fuel utilization, possibly over 85 percent, through the assurance of heat energy that is exactly suitable for HVAC-system consumption. Also the produced heat is appropriate to run absorption chillers, whose chilling characteristics are again suitable for HVAC systems. In addition, parallel continuous electricity production can guarantee the required power for the operation of all equipment within the HVAC system, and eventually surplus energy can be used at the location or transfered to the public grid.

Due to the high efficiency of fuel utilization and the use of natural gas or some other environmental advantageous fuels, cogeneration plants have low CO_2, SO_2 and NO_X emissions, so these systems contribute considerably to the protection of the environment. Taking into account these facts, as well as permanent need for the construction of new power energijskega gospodarjenja, investicijske realizacije in varstva okolja, v razviti državah dandanes pogosto uporabljajo opisane sisteme.

Zares pri vpeljivosti postrojenja ne smemo spregledati možne vpeljave kogeneracijskih in trigeneracijskih sistemov, kar pomeni analizo gospodarskih in finančnih prednosti v primerjavi s tradicionalnimi OPK sistemi. Prispevek prikazuje poenostavljen gospodarski model in prav tako primer konkretnega projekta z gospodarskimi rezultati kogeneracije ter sedanji OPK sistem v bolnišnici na Hrvaškem. Kogeneracija ali boljše trigeneracija je najprimernejša tehnologija za proizvodnjo elektrike, toplote in hladilne energije. Investicijski odplačilni čas podobnih OPK sistemov je, glede na izkušnje iz Zahoda, med štirimi in šestimi leti. Opisan sistem je odvisen od velikosti postrojenja, vračila investicije v času 3,3 do 3,6 let, pomembna je njena občutljivost na izstopne parametre (cene plina in elektrike). Nespremenjeni projekti v nenaklonjenih okoliščinah lahko povrnejo investicijo najkasnje po devetih letih.

Vsi omenjeni razlogi upravičujejo vpeljavo kogeneracijskih in trigeneracijskih OPK sistemov. Pred končnimi sklepi pa je treba izvesti podrobne analize.

plants and thermal units, as well as due to the increasingly rigorous demands on energy management, rationalization of investments and environment protection, these described systems are nowadays frequently used in developed countries.

Indeed, the viability of the plant should not overlook the potential implementation of cogeneration and trigeneration systems, which means an analysis of the economic and financial advantages in comparison with traditional HVAC systems. The paper gives a simplified economic model, as well as an example of cogeneration introduction in an existing HVAC system in a hospital in Croatia. Results indicate that cogeneration, or better trigeneration, is the most appropriate technology for electricity, heat and cooling energy production. The investment payback period of such HVAC systems is, according to experience, between four and seven years. The described example, depending on the plant size, would pay for itself in 3.3 to 3.6 years, but this is sensitive to input parameters (gas and electricity prices).

The implementation of cogeneration and trigeneration in HVAC systems is justified but it is necessary is to perform detailed viability analyses prior to a final decision.

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Koncentracija radona v prezračevanih notranjih prostorih v Hong Kongu

The Radon Concentration in a ventilated Indoor Space in Hong Kong

Zhang Lin - Tin-tai Chow - T.C. Wong

Stopnja zločanja radona je veliko večja za gradbene materiale iz Hong Konga v primerjavi z materiali iz drugih območii. Izpostavljanje visokim stopnjam sevanja radona pomeni resno ogrožanje zdravja. Za namen izpeljave analize notranje koncentracije radona je bilo predpostavljeno, da se ti materiali pojavljajo na tleh, stenah in stropu. Stopnjo notranjega sevanja radona v zraku lahko določimo ˝ročno˝ in s simuliranjem dinamike fluida, tako da z različnimi stopnjami izmenjavanja zraka izračunamo vpliv stopnje ventilacije na količino radona notranjega zraka. Rezultati kažejo, da stopnja prezračevanja igra pomembno vlogo pri nadzoru notranje koncentracije radona. Radon v pisarnah v splošnem ni glavni dejavnik pri določanju stopnje prezačevanja, čeprav je priporočljivo obdržati čim nižjo stopnjo le-tega.

(Ključne besede: prezračevanje prostorov, koncentracije radona, materiali gradbeni, analize)

The radon emanation rate has been found to be much higher for building materials from Hong Kong compared with those from other places. Exposure to high radon levels poses a serious health risk. For the purpose of carrying out A worst-case analysis of the indoor radon concentration it was assumed that no finishing materials are applied to the floor, walls and ceiling. The level of indoor radon radiation in the air is studied by hand calculation and Computational Fluid Dynamics simulation using different air exchange rates to evaluate the influence of ventilation rate on the indoor-air radon level. Results show that the ventilation rate plays a very important role in controlling the indoor radon concentration. It is concluded that radon in offices is, in general, not a major factor when considering ventilation rate, although it is always advisable to keep the radon level as low as practically possible.

(Keywords: ventilation, indoor radon concentration, building materials, analysis)

0 UVOD

Večina poslopij v Hong Kongu je visoke konstrukcije, zato delež radona na tleh le malo prispeva k notranji stopnji le-tega. Granit in beton sta zelo uporabljena gradbena materiala v Hong Kongu, v teh materialih pa je stopnja izločanja radona zelo velika. Stopnja izločanja radona betona je 21×10^{-6} $Bqkg^{-1}s^{-1}$ in opeke 13×10^{-6} $Bqkg^{-1}s^{-1}$ [13]. Stopnja izločanja radona teh gradbenih materialov je v drugih območjih dosti nižja [12]. Notranje povečanje količine radona je posledica izločevanja radona iz gradbenih materialov v Hong Kongu, kar se razlikuje od stanja v ZDA in evropskih državah [9].

Skoraj vse pisarne v Hong Kongu so v visokih stavbah in imajo osrednjo klimatizacijo. Veliko od njih ima okna, ki se jih ne da odpreti, kar pomeni, da naravno prezračevanje ni mogoče. Trenutno si inženirji prizadevajo, da bi se izognili pritožbam glede

0 INTRODUCTION

Most buildings in Hong Kong are high-rise structures and so soil re-entry of radon gas has only a relatively small contribution to the indoor radon level. Granite and concrete are widely used as building materials in Hong Kong, and the radon emanation rate from these materials has been found to be high. The radon emanation rate from concrete has been found to be 21×10^{-6} $Bqkg^{-1}s^{-1}$ and that of brick is 13×10^{-6} $Bqkg^{-1}s^{-1}$ [13]. The radon emanation rate of similar building materials which come from other places are much lower [12]. The indoor radon build-up comes mainly as a result of radon emission from building materials in Hong Kong, which is different from the situation in the United States and European countries [9].

Almost all the offices in Hong Kong are located in high-rise buildings and adopt central air-conditioning. Many of them only have fixed windows, i.e. no natural ventilation is available. To avoid any indoor-air quality complaints, there is a trend for slabega zraka, postaviti na koncu dovodne odprtine dušilnik, ki bo omogočal stalen dotok, tako da bo največja količina zunanjega zraka vedno vsem na voljo, čeprav je v nasprotju s primarnim ciljem varčevanja energije.

Raziskave radona na širšem območju v notranjih prostorih v letih 1992/93 in 1995/96 je opravil Oddelek za varovanje okolja v Hong Kongu, te so pokazale koncentracijo radona v pisarnah.

Radon je radioaktiven plin brez okusa in vonja. Nastane, ko se radij topi v nekaterih prsteh in kameninah, posebej v granitu, radioaktivno razpada.

Izpostavljanje kombinaciji tobačnega dima in visoki stopnji radona pomeni resno ogrožanje zdravja. Kadilec cigaret ima trikrat večjo možnost obolenja za pljučnim rakom od nekadilca, ki je izpostavljen visoki stopnji radona. Glede na izračune je bilo v Hong Kongu leta 1986 od vseh smrti za pljučnim rakom 13% tistih, ki jih je povzročil radon.

Nivo radona je bil najvišji v Hong Kongu v primerjavi z drugimi mesti po svetu [4]. Povprečna koncentracija radona v pisarnah, tovarnah, šolah, javnih mestih in bolnišnicah je bila 77 Bq/m^3, 76 Bq/m^3, 43 Bq/m^3, 64 Bq/m^3 in 55 Bq/m^3 [12]. Izračuni nedavnih raziskav so pokazali, da je samo 5,1 % javnih mest preseglo 200 Bq/m^3 ([4] do [6]). Priporočena stopnja koncentracije notranjih prostorov v ZDA je 150 Bq/m^3 [2].

engineers to put a constant-flow damper at the intake end so that the maximum amount of outdoor air is always provided to the occupied area, although this defeats the prime objective of energy saving.

Territory-wide indoor radon surveys were conducted by the Hong Kong Environmental Protection Department in 1992/93 and 1995/96. The indoor radon concentration in Hong Kong offices was found.

Radon is a radioactive gas with no taste, smell nor odour. It is formed when radium found in most soils and rocks, particularly granite, disintegrates radioactively.

Exposure to a combination of tobacco smoke and high radon levels poses a serious health risk. A cigarette smoker runs three-times greater risk of getting lung cancer than non-smokers exposed to high radon levels. According to a relative risk model, the calculated number of radon-induced lung-cancer deaths in Hong Kong in 1986 was about 13% of the total number of lung-cancer deaths for the year.

The radon level has been confirmed to be on the high side is comparison to many cities in the world [4]. The average radon concentrations for offices, factories, schools, public places and hospitals were 77Bq/m^3, 76 Bq/m^3, 43Bq/m^3, 64Bq/m^3 and 55Bq/m^3, respectively [12]. The figures for recent surveys showed that only 5.1% of public-place premises exceeded 200Bq/m^3 ([4] to [6]). The recommended action level for indoor radon concentration in the United States is 150 Bq/m^3 [2].

1 TEORIJA

1 THEORY

Spremembo koncentracije radona s stopnjo izmenjavanja zraka lahko ponazorimo z naslednjo enačbo:

The variation of radon concentration with air-exchange rate can be illustrated by the following equation:

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \lambda C + \frac{\sum E_j A_j}{V} + \frac{q(C_0 - C)}{V} \quad (1)$$

$$C = \left(C_i - \frac{\sum E_j A_j + qC_0}{V\left(\lambda + q/V\right)} \right) e^{-\left(\lambda + \left(q/V\right)\right)t} + \frac{\sum E_j A_j + qC_0}{V\left(\lambda + q/V\right)} \quad (2).$$

Ker je $\lambda << \frac{q}{V}$, je ustaljena rešitev naslednja:

Since $\lambda << \frac{q}{V}$, the steady-state solution becomes:

$$C_{(\infty)} = C_0 + \frac{\sum E_j A_j}{q} \quad (3).$$

Iz enačbe (3) vidimo, če ima stavba veliko število izmenjav zraka, potem je koncentracija radona zunaj in znotraj poslopja približno enaka. Izraz $\Sigma E_j A_j$ je v povezavi s kritično rastjo krivulje radona v prostorih, ko je C_i blizu C_0.

Diferencialna enačba (2) z upoštevanjem časa, ko gre ta proti nič, je naslednja:

From equation (3), if a building is under strong ventilation conditions, the indoor radon concentration is approximately the same as the outdoor radon concentration. The emission term $\Sigma E_j A_j$ is related to the critical radon growth curve at the premises if C_i is assumed to be close to C_0.

Differentiating equation (2) with respect to time and taking t to approach zero, the following equation is obtained:

$$M_i = \frac{dC}{dt}\Big|_{t \to 0} = \frac{\sum E_j A_j}{V} \quad (4).$$

Potem je:

Then:

$$\Sigma E_i A_i = M_i V \quad (5).$$

Enačbo (5) vstavimo v enačbo (3):

Equation (5) was substituted into equation (3):

$$C_{(\infty)} = C_0 + \frac{M_i}{q}$$

ali

or

$$\frac{C_{(\infty)}}{C_0} = 1 + \frac{M_i}{C_0(ACH)} \quad (6).$$

2 NDT SIMULIRANJE

Za proučevanje zračnih tokov in onesnaženega zraka v stavbah imamo na voljo dva postopka: eksperimentalno raziskavo in računalniško simuliranje. Najbolj stvarne informacije glede notranjih zračnih tokov in onesnaženega zraka dajo neposredna merjenja, to so: porazdelitev hitrosti zraka, temperatura, relativna vlažnost in stopnja onesnaženosti. Ker morajo biti ta merjenja opravljena na več krajih, so neposredna merjenja porazdelitve zelo draga in vzamejo veliko časa. Celotno merjenje lahko zahteva več mesecev dela. Za dosego končnih rezultatov morajo biti dovod zračnih tokov in temperatura iz hladilnih, prezračevalnih in klimatskih sistemov (HPK - HVAC) ter temperature prostorov stalne med celotnim merjenjem. To je še posebej težko doseči, saj se zunanji pogoji časovno spreminjajo in se glede na to spreminjajo tudi temperature prostorov, zračni tok in temperature iz sistemov HPK.

Zračni tok in onesnažen zrak lahko določimo z rešitvijo več enačb, ki upoštevajo tok, energijo in onesnaženje v sistemu. Zaradi omejitev pri eksperimentalnem postopku, zmogljivejših računalnikih numerična rešitev teh enačb omogoča preprosto izbiro za določanje zračnega toka in porazdelitve onesnaženosti v stavbah. Ta metoda se imenuje NDT (numerična dinamika tekočin).

Metoda NDT je zelo uporabna za analizo notranjega okolja, kakor so vzorec zračnega toka in porazdelitev hitrosti zraka, temperatura, intenzivnost turbulence in koncentracija onesnaženosti. Zaradi omejene moči in zmožnosti računalnika mora biti model turbulence uporabljen v tehniki NDT, da bi rešili problem gibanja toka. Uporaba modelov turbulence vodi k nezanesljivosti izračunanih rezultatov, ker modeli niso splošni. Zato je pomembno, da v ta program vnesemo eksperimentalne podatke [15].

Model NDT, ki temelji na modelu RNG *k*-e in funkciji zidu [11], je bil uporabljen pri zbiranju podatkov za značilno pisarno v Hong Kongu (sl. 1). Celoten prostor mora biti razvrščen v omejene prostornine po mrežnem sistemu. Spremenljivke toka, kakor so hitrost, temperatura in koncentracija,

2 CFD SIMULATIONS

Two main approaches are available for the study of airflow and pollutant transport in buildings: experimental investigation and computer simulation. In principle, direct measurements give the most realistic information concerning indoor airflow and pollutant transport, such as the distributions of air velocity, temperature, relative humidity, and contaminant concentrations. Because the measurements must be made at many locations, direct measurements of the distributions are very expensive and time consuming. A complete measurement may require many months of work. Moreover, to obtain conclusive results, the supply airflow and temperature from the Heating Ventilating and Air Conditioning (HVAC) systems and the temperatures of the building enclosure should be kept unchanged during the experiment. This is especially difficult to achieve because the outdoor conditions change with time and the temperatures of the building enclosure and the airflow and temperature from the HVAC systems will also change accordingly.

Alternatively, the airflow and pollutant transport can be determined computationally by solving a set of conservation equations describing the flow, energy, and contaminants in the system. Due to the limitations of the experimental approach and the increase in performance and affordability of high-speed computers, the numerical solution of these conservation equations provides a practical option for determining the airflow and pollutant distributions in buildings. The method is the Computational Fluid Dynamics (CFD) technique.

The CFD technique is a powerful tool to analyse indoor environment problems, such as airflow pattern and the distributions of air velocity, temperature, turbulent intensity, and contaminant concentrations. Due to limited computer power and capacity available at present, turbulence models have to be used in the CFD technique in order to solve flow motion. The use of turbulence models leads to uncertainties in the computed results because the models are not universal. Therefore, it is essential to validate a CFD program with experimental data [15].

A validated CFD model based on the RNG *k*-ε model and wall function [11] was used to generate data for a typical office in Hong Kong (Figure1). The whole computational domain, the space of the room, needs to be divided into a number of finite volumes using a grid system. The flow variables, such as velocity, temperaso računani na sredini omejene prostornine. Pri manjši omejeni prostornini so rezultati bolj natančni, kar pa pomeni več časa za izračun.

Prostornina, površina tal in površina sevanja radona v modelu pisarne so bili 48,93 m^3, 20,07 m^2 in 79,15 m^2. Predpostavljeno je bilo, da sta v pisarni dve osebi (oseba 1, oseba 2). Tam sta bili dve dovodni in ena odvodna rešetka, nameščene na stropu. Z uporabo ventilatorja je bil doveden 100% svež zrak, s prilagodljivo stopnjo prezračevanja v pisarno prek dovodnih rešetk. Predpostavljeno je bilo, da so vsa vrata in okna zaprta in se zrak odvaja prek odvodne rešetke. Radon je seval z betonske površine in notranja koncentracija radona se je postopno povečevala do določenega nivoja glede na različne stopnje izmenjav zraka. Imamo tri strategije za nadzor radona v notranjih prostorih: z večanjem stopnje izmenjavanja zraka, z zmanjševanjem dotoka radona in s povečanjem odstranitve notranjega radona. Za študijo je bila izbrana prva strategija.

Simuliranje je temeljilo na 0,5 izmenjav zraka na uro (IZU - ACH), 1,3 IZU in 4 IZU za določitev porazdelitve radona v prostoru. Koncentracija radona v prostoru je bila ocenjena pri 1,2 m od tal, kar naj bi pomenilo cono dihanja v sedeči legi.

Prejšnje raziskave so potrdile, da različni končni gradbeni materiali (npr. plastična tapeta) učinkovito zmanjšujejo koncentracijo radona v prostoru [7]. Da bi naredili analizo z največjimi koncentracijami radona, so v tej raziskavi na tleh, stenah in stropu opustili končne gradbene materiale. Izraz za notranjo koncentracijo radona (Bq/m^3) z določeno spremembo zraka na uro z dano stopnjo rasti radona M_i je definirana z enačbo 6.

V enačbi uporabimo $\rho_{betona} = 2450$ kgm^{-3}, $x_j = 0{,}125$ m, $E_{betona} = 21x10^{-6}$ $Bqkg^{-1}s^{-1}$ [3], $C_0 = 15$ Bq/m^3, $C_{(\infty)} = 200$ Bq/m^3, $A_j = 79{,}12$ m^2, $V = 48{,}93$ m^3 in dobimo oceno za stopnjo rasti radona m_i približno 74,90 Bqm^3h^{-1}.

ture and concentration, are solved at the centre of each finite volume. The finer the grid is, the more accurate the results will be. However, fine grid will require more computing time and capacity.

The volume, floor area and radon-emitting surface area of the office model were 48.93m^3, 20.07m^2 and 79.15m^2 respectively. It was assumed that 2 occupants (named occupant 1 and occupant 2) were inside the office. There were two supply air grilles and one return air grille installed in the ceiling. With the use of a fan, 100% fresh air with an ajustable ventilation rate was supplied to the office via the supply air grilles. It was assumed that all the doors and windows were closed and that the air was discharged through the return air grille. The radon was emitted from the concrete surface and the indoor radon concentration was gradually accumulated up to a steady level under different air-exchange rates. There are 3 strategies for controlling indoor radon: by increasing the air replacement rate; by lowering the input rate of radon and increasing the indoor removal rate. The first of these will be selected for the study.

The simulation was based on 0.5 air changes per hour (ACH), 1.3 ACH and 4 ACH to determine the radon-gas distribution inside the room. The indoor radon concentration was evaluated at 1.2 m from the floor to simulate the breathing height of a person seated in the room.

Previous studies have confirmed that different finishing materials (e.g. plastic wallpaper) effectively reduce the indoor radon concentration [7]. For the purpose of carrying out the worst case analysis of the indoor radon concentration it was assumed in this study that no finishing materials were applied to the floor, wall or ceiling. The formula for the indoor radon concentration (Bq/m^3) for a definite air change per hour with a given radon growth rate (M_i) is defined by Equation 6.

Applying this equation with $\rho_{concrete} = 2450$ kgm^{-3}, $x_j = 0.125$ m, $E_{concrete} = 21x10^{-6}$ $Bqkg^{-1}s^{-1}$ [3], $C_0 = 15$ Bq/m^3, $C_{(\infty)} = 200$ Bq/m^3, $A_j = 79.15$ m^2, $V = 48.93$ m^3, gives an estimate for the radon growth rate (m_i) of approximately 74.90 Bqm^3h^{-1}.

$$\frac{C_{(\infty)}}{C_0} = 1 + \frac{m_i}{C_0(ACH)}$$

$$\frac{200}{15} = 1 + \frac{74{,}90}{15(ACH)}$$

$$ACH = 0{,}4\ h^{-1}$$

V tem primeru je najmanjše število izmenjav zraka na uro približno 0,4 za zagotovitev, da stanovalca nista izpostavljena notranji koncentraciji radona, ki znaša maksimalno 200 Bq/m^3.

Thus, the minimum number of air changes per hour to ensure that the occupants are not subject to a high level of indoor radon concentration (200 Bq/m^3) as approximately 0.4.

3 REZULTATI IN RAZPRAVA

Notranja koncentracija radona za osebi 1 in 2 je prikazana glede na stopnjo prezračevanja na sliki 2. Sobna koncentracija radona z različnimi stopnjami izmenjav je prikazana na slikah 3 do 8.

3 RESULTS AND DISCUSSION

The indoor radon concentration for occupants 1 and 2 are plotted against the ventilation rate and the result is presented in Figure 2. The room's radon concentration with different exchange rates is shown

Prereza *X-X′* in *Y-Y′* pisarne sta prikazana na sliki 1.

Masa plina v radonu glede na celotno količino zraka:

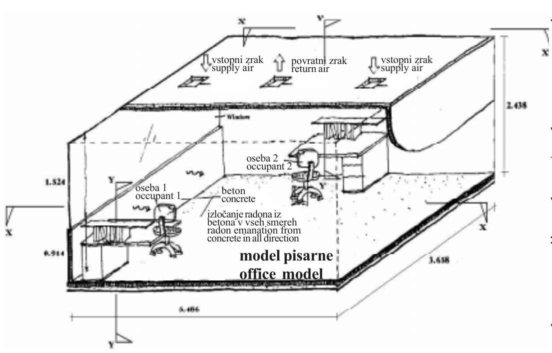
in Figure 3 to 8. The positions of Section *X-X'* and *Y-Y'* are shown in Figure 1.

The mass fraction of radon gas is the mass of radon divided be the total mass of the air mixture:

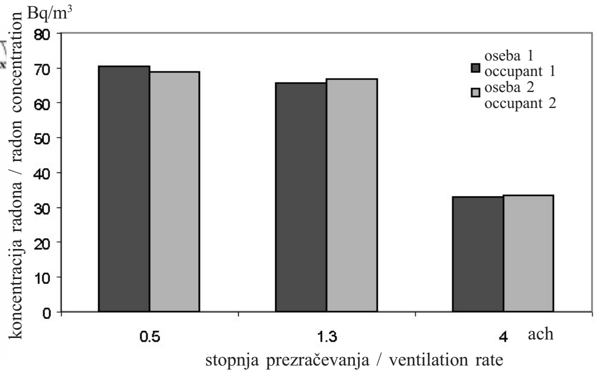
$$1\text{Bq}/\text{m}^3 = \frac{1\times 1{,}6\times 10^{-20}\times 9{,}96}{1\times 1{,}205} = 1{,}3225\times 10^{-19}\ \text{kg}/\text{kg}$$

kjer je gostota plina radona in zraka 1,6 x 10^{-20} kg/m^3 in 1,205 kg/m^3 [4].

where the density of radon gas and air are 1.6 × 10^{-20} kg/m^3 and 1.205 kg/m^3, respectively [4].



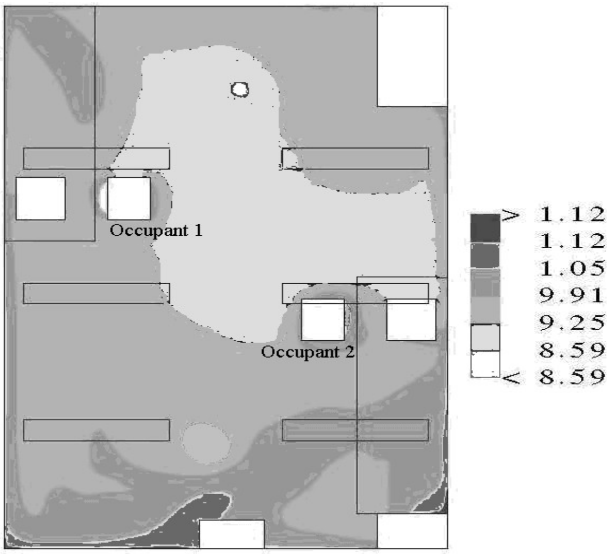
Sl. 1. *Izmere in razporeditev pisarne*
Fig. 1. *Model office dimensions and layout*



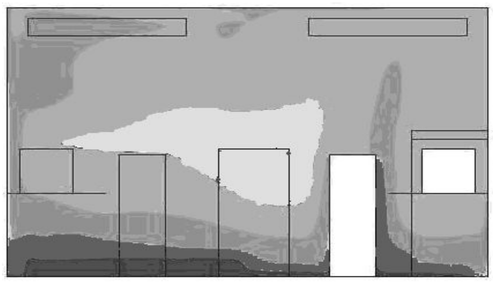
Sl. 2. *Sprememba notranje koncentracije radona kot IZU za osebo 1 in 2*
Fig. 2. *Variation of indoor radon concentration vs ACH for occupants 1 and 2*

Na sliki 2 je zelo jasno vidna usmeritev, da se stopnja radona zmanjšuje s stopnjo izmenjavanja zraka. S stopnjo izmenjavanja zraka 0,5 IZU je največja koncentracija radona enaka 70 Bq/m^3 in 68,5 Bq/m^3 za osebi 1 in 2, kar je veliko manj od 200 Bq/m^3 – priporočena stopnja. Poleg tega je koncentracija radona za osebi 1 in 2 več ali manj enaka, ko jo primerjamo z učinki prezračevanja.

In Figure 2, a very clear trend was observed, the radon level decreased with air-exchange rate. With an air-exchange rate of 0.5 ACH, the maximum radon concentration is found to be equal to 70 Bq/m^3 and 68.5 Bq/m^3 for occupants 1 and 2, respectively. These levels are much lower than the 200 Bq/m^3 recommended action level. Additionally, the radon concentration for occupants 1 and 2 is more-or-less the same when compared with the effect of ventilation.



Sl. 3. *Sobna koncentracija radona v Bq/m^3 pri 0,5 stopnji izmenjavanja zraka in višini 1,2 m (prerez X-X′)*
Fig. 3. *Room radon concentration in Bq/m^3 at 0.5 air-exchange rate and 1.2 m height (Section X-X')*



Sl. 4. *Sobna koncentracija radona v Bq/m^3 pri 0,5 stopnji izmenjavanja zraka (prerez Y-Y′)*
Fig. 4. *Room radon concentration in Bq/m^3 at 0.5 air-exchange rate (Section Y-Y')*

Na slikah 3 in 4 vidimo, da se sobni zrak redno toda počasi zamenjuje z zunanjim zrakom s procesom izmenjavanja zraka. Zaradi te skrajno nizke stopnje izmenjavanja zraka je kroženje zraka majhno in zato so se pojavile v kotih pisarne mrtve cone s sorazmerno visoko koncentracijo radona. V splošnem je srednja vrednost koncentracije radona približno 70 Bq/m^3, največja vrednost je le 90 Bq/m^3. Najvišja vrednost se je pojavila le v kotih pisarne, kjer pa se ljudje ne zadržujejo.

S povečanjem stopnje izmenjavanja zraka na 1,3 ACH (2,6 krat) se koncentracija radona zmanjša le za 8%. Količina radona v sobi je bila pod 70 Bq/m^3 pri 1,2 m nad tlemi, kakor je prikazano na sliki 5. Pri tej stopnji izmenjavanja zraka v določeni sobi je stopnja izmenjavanja svežega zraka 7,5 litrov/osebo/sekundo, kar je zahtevani minimum po standardu ASHRAE 62-1989R.

S primerjavo slik 3 do 6 opazimo razliko v zmanjšani koncentraciji radona in na slikah 7 in 8 je povprečna koncentracija radona 32 Bq/m^3. Ta izredno nizka stopnja koncentracije radona je posledica razmeroma visoke stopnje izmenjavanja zraka, ki tako ″izčrpava″ visoko stopnjo koncentracije iz prostora.

Lokacija in število teh dovodnih/odvodnih rešetk, lega pisarne itd. bodo vplivali samo na porazdelitev radona v pisarni in ne na koncentracijo radona v pisarni.

Ta model pa ima tudi omejitve. Kot prvo je bilo predpostavljeno, da je zunanja koncentracija radona nespremenljiva pri 15 Bq/m^3, vendar se le ta spreminja. Na zunanjo stopnjo

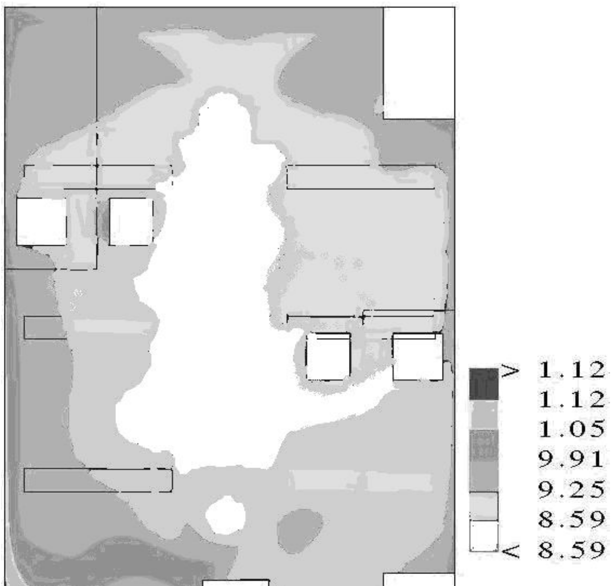
From Figure 3 and 4, we can see that the room air is constantly but slowly replaced by outdoor air via a forced-air-exchange process. With this extremely low air-exchange rate, the air circulation is low and some dead zones of relatively high radon concentration were found in the corners of the room. In general, the mean radon concentration is around 70 Bq/m^3 with the maximum value being only 90 Bq/m^3. The high values of radon concentration occurred at the corners of the room where the occupants are unlikely to be located for extended periods.

By increasing the air exchange rate to 1.3ACH (2.6 times), there is only a slight decrease of 8% in the radon concentration. However, a larger portion of the room's radon concentration was found to be below 70 Bq/m^3 at 1.2 m above the floor, as shown on Figure 5. Under this air-exchange rate and in this particular room, the fresh-air rate is about 7.5 litres/person/second, which is the minimum requirement as specified by the revised ASHRAE standard 62-1989R.

In compared with Figure 3 to 6, there is a marked decrease in the radon concentration in Figure 7 and 8 with an average radon concentration of around 32 Bq/m^3. This excessively low level of radon concentration was due to the relatively high air-exchange rate which brought in outdoor air of low radon concentration and exhausted the indoor air of relatively high radon concentration.

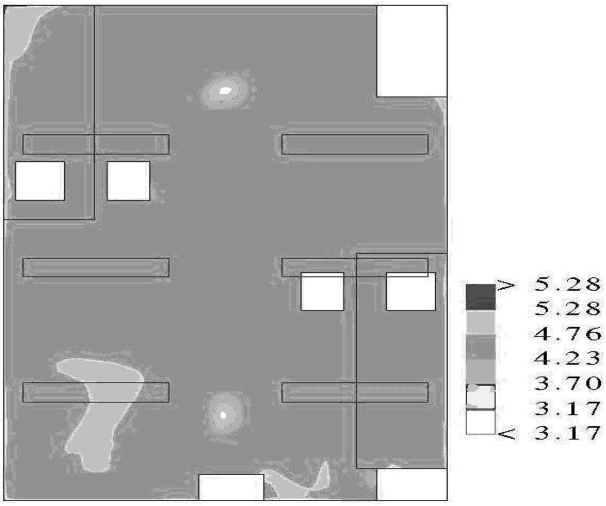
The location and number of the supply/return air grills, layout of the room, etc., will only affect the room's radon distribution, but not the overall radon concentration.

There are limitations in the model itself. First, it was assumed that the outdoor radon concentration is kept constant at 15Bq/m^3. However, it varies from place to place. The outdoor radon level is affected by meteo-



Sl. 5. *Sobna koncentracija radona v Bq/m^3 pri 1,3 stopnji izmenjavanja zraka in višini 1,2 m (prerez X-X')*
Fig. 5. *Room radon concentration in Bq/m^3 at 1.3 air-exchange rate and 1.2 m height (Section X-X')*

Sl. 6. *Sobna koncentracija radona v Bq/m^3 pri 1,3 stopnji izmenjavanja zraka (prerez Y-Y')*
Fig. 6. *Room radon concentration in Bq/m^3 at 1.3 air-exchange rate (Section Y-Y')*



Sl. 7. *Sobna koncentracija radona v Bq/m³ pri 4,0 stopnji izmenjavanja zraka in višini 1.2 m (prerez X-X')*
Fig. 7. *Room radon concentration in Bq/m³ at 4.0 air-exchange rate and 1.2 m height (Section X-X')*

Sl. 8. *Sobna koncentracija radona v Bq/m³ pri 4,0 stopnji izmenjavanja zraka (prerez Y-Y')*
Fig. 8. *Room radon concentration in Bq/m³ at 4.0 air-exchange rate (Section Y-Y')*

radona vplivajo meteorološke, topografske in geološke razmere [8]. Razlike so v zunanjem radonu, ki ga povzročajo dnevne spremembe. Najvišja koncentracija se pojavi ob zori, najnižja pa popoldne.

Model ne upošteva odvisnosti sevanja radona različnih gradbenih materialov. Različni gradbeni materiali povzročajo različne stopnje sevanja radona. Kakorkoli že so ti učinki zelo majhni v primerjavi s tistimi, ki jih povzročajo različni prezračevalni sistemi [14].

4 SKLEPI IN PRIPOROČILA

Ena od možnosti za zmanjšanje notranje stopnje radona je v dovajanju več svežega zraka v prostor, vendar s tem porabimo več energije.

Po pravilniku Hong Konga o stavbah iz leta 1984 je najmanjša stopnja svežega zraka za vsako nadstropje stavbe, ki je uporabljeno za pisarne oziroma stanovanja, dana s prezračevanjem, ki zagotavlja pet izmenjav na uro.

Ocenjena stopnja svežega zraka je bila daleč pod zahtevano količino. Tako lahko menimo, da radon v pisarnah v splošnem ni glavna skrb, čeprav je priporočljivo obdržati stopnjo radona na čim nižji ravni.

Kakorkoli že, zamisel je uporabna za inženirje, ki z izbiro prezračevanja, ki temelji na stopnji svežega zraka na osebo, učinkovito vplivajo na zmanjšanje deleža radona. Ustrezna stopnja prezračevnja pomeni pomemben dejavnik pri zmanjševanju notranje stopnje radona.

Glede na raziskavo 3 v letih 1995/96 ni nobena pisarna, ki je bila vključena v raziskavo presegla meje 200 Bq/m³, največja vrednost je bila

rological, topographical and geological conditions [8]. There will be a difference in the outdoor radon caused by the diurnal variation where the radon level peaks at dawn and reached its lowest value in the afternoon.

In addition, the model does not take into account the correlation between the radon emanation rate of different building materials. Different building materials will have different effects on the radon emanation rates which determine the indoor radon concentration. However, these effects have been found to be small when compared to those caused by different ventilation conditions [14].

4 CONCLUSIONS AND RECOMMENDATIONS

One of the ways to reduce the indoor radon level is to introduce more fresh air to the room. However, this will consume more energy.

According to the Hong Kong Building Regulations 1984, the minimum fresh-air rate for every storey of a building used as an office or habitation should be provided with ventilation enabling not less than 5 air changes per hour.

Since the estimated fresh-air rate is far below the amount required it can therefore be concluded that radon in the office is, in general, not a major concern, although it is always advisable to keep the radon level as low as practically possible.

The concept, however, seems to be useful as building-services engineers may develop a rule of thumb by picking up a certain ventilation limit based on fresh-air rate per person, so that radon mitigation can be carried out effectively. An adequate ventilation rate has been shown to be a powerful factor in reducing the indoor radon level.

According to the 1995/96 survey 3, is no surveyed office premises exceeded the 200 Bq/m³ limit, with the maximum value being 156 Bq/m³. The high

156 Bq/m^3. Visoka stopnja radona je nastala zaradi neustreznega prezračevanja in prekomerne gostote, kar je bilo ugotovljeno v tej študiji pa tudi v drugih raziskovalnih delih, npr. HKPED 1998. Srednja vrednost koncentracije radona v pisarnah je bila 77 Bq/m^3 in 80 Bq/m^3 v letih 1995/96 in 1992/93 [12]. Podobni rezultati so bili dobljeni tudi s simulacijo te raziskave.

level of radon was found to be caused by inadequate ventilation and excessive occupancy density, which was not only the finding of the present study, but also other research works, *e.g.* HKPED 1998. The mean radon concentration for the office was found to be 77 Bq/m^3 and 80 Bq/m^3 in 1995/96 and 1992/93 surveys, respectively [12]. The values found are similar to the simulation results of this study.

5 OZNAČBE
5 NOMENCLATURE

stopnja izmenjavanja zraka na uro	*IZU - ACH*	h^{-1}	air-exchange (ventilation) rate per hour
površina gradbenega materiala v prostoru	A_j	m^2	surface area of building material in the room
notranja koncentracija radona	C	Bq/m^3	indoor radon concentration
začetna notranja koncentracija radona	C_i	Bq/m^3	initial indoor radon concentration
izenačenje notranje koncentracije radona	$C_{(\infty)}$	Bq/m^3	equilibrium indoor radon concentration
zunanja koncentracija radona	C_0	Bq/m^3	outdoor radon concentration
stopnja sevanja radona gradbenega materiala j	E_j	Bqm^{-2}h^{-1}	radon emanation rate of building material j
stopnja rasti radona	M_i	Bqm^{-3}h^{-1}	radon growth rate
dotok svežega zraka	q	m^3/s	fresh air supply
dejanska prostornina pisarne	V	m^3	effective volume of the room, m^3
čas	t		time
debelina gradbenega materiala j	x_j	m	thickness of building material j
specifična teža gradbenega materiala j	ρ_j	kgm^{-3}	density of building material j
količina radona v volumnu	λ		volumetric radon generation

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Določanje porabe energije gospodinjstev v okviru regionalnega načrtovanja porabe

The Determination of Household Energy Consumption as a Part of a Regional Energy Plan

Bernard Franković - Kristian Lenić

V tem prispevku je analizirana poraba energije gospodinjstev v okviru regionalnega načrtovanja porabe. Raziskava je bila opravljena za Primorsko-goransko območje na Hrvaškem. Ta analiza je temeljila na raziskavi gospodinjstev z metodo prostorske razdelitve. Za ta namen je bila regija posebej razdeljena v 14 con, ki so bile določene glede na geografske, klimatske in ekonomske značilnosti kakor tudi glede na različno gostoto poseljenosti in urbanizacije. Analiza je obsegala izračune za celotno porabo energije za celotno regijo in tudi za vsako posamezno cono. Še več, analizirali so energijske vire in uporabo le-te za ogrevanje, pripravo tople sanitarne vode, kuhanje ter drugo. Predstavljeni so bili tudi nekateri parametri, npr.: število družinskih članov, gospodinjskih aparatov ter avtomobilov, ki so odvisni od življenjskega standarda, toda so tudi v povezavi s porabo energije. Rezultati te raziskave so osnova za pripravo projekta plinifikacije v regiji.

(Ključne besede: gospodinjstva, poraba energije, analize porabe, strukture porabe)

In this paper we analyse household energy consumption as part of a regional energy plan. The research has been performed in the area of the Primorsko-goranska County, Croatia. The analysis was based on a survey of households using a spatial division methodology. The region was divided into 14 zones based on geographic, climatic and economic characteristics as well as different population concentrations and urbanization. The analysis included a calculation of the total energy consumption for the whole region as well as for each zone. In addition, the total energy consumption has been analyzed in tems of energy sources and use of this energy for space heating, domestic hot-water preparation, cooking and non-thermal usage. Some additional parameters whhich relate to living standard and energy consumption, such as the number of household members and the number possession of household devices and cars have also been included. The results of the research are a basis for the project to intorduce gas to the region.

(Keywords: households, energy consumption, energy consumption analysis, consumption structures)

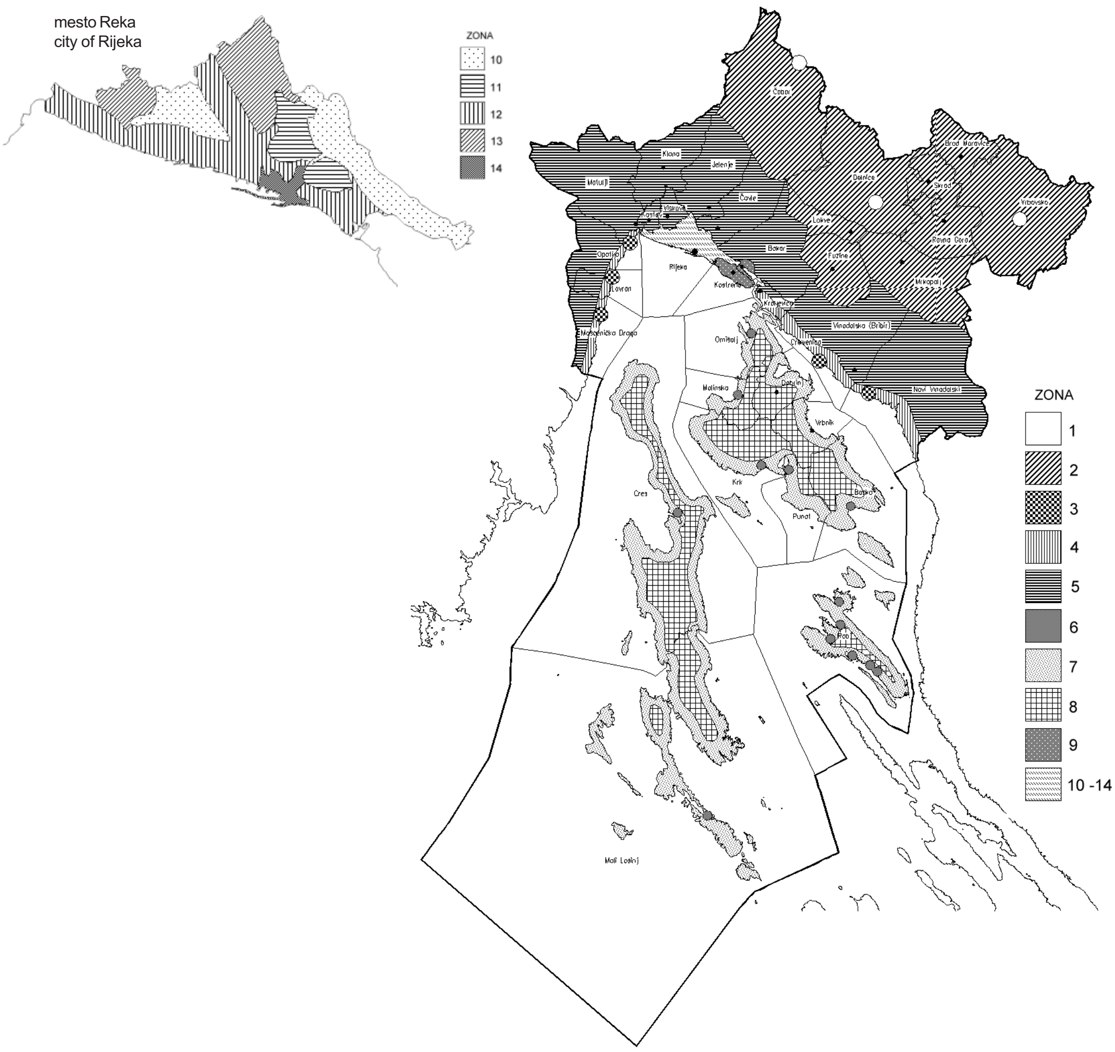
0 UVOD

Projekt plinifikacije Primorsko-goranskega območja na Hrvaškem vključuje raziskavo in končne izračune energije v gospodinjstvih, industriji in javnih področjih. Ocena energijskih potreb je bila temelj za izračun končne porabe energije v gospodinjstvih. Predstavljeni vzorec je vključeval 2083 gospodinjstev, vsako od njih je sodelovalo z izpolnitvijo vprašalnika. Ta izbrani vzorec je vključeval 1,8% vseh gospodinjstev v Primorsko–goranskem okrožju in približno 2% prebivalstva. Za ta namen je bila regija razdeljena v 14 con, ki so bile določene glede na geografske, klimatske in ekonomske značilnosti, pa tudi glede na različno gostoto prebivalstva in urbanizacije. Število

0 INTRODUCTION

The project to introduce gas to the Primorsko-goranska County in Croatia includes research and calculations of the total energy requirements for households, industrial and public-service sectors of the County. A survey of the energy needs was the basis for a calculation of the total energy consumption of the households. Our survey encompassed 2083 households and every household was represented by a questionnaire. This representative sample comprises 1.8 % of the total number of households in Primorsko-goranska County and about 2% of the inhabitants. The region was divided into 14 zones based on geographic, climatic and economic characteristics as well as different population concentrations and urbanization. The number of surveyed households in a zone was calculated from proučevanih gospodinjstev v coni je bilo določeno glede na odstotek števila prebivalcev, razen v tistih conah, kjer je poseljenost majhna. Tam je bilo vključenih petdeset gospodinjstev. Območje mestne občine Reke je bilo razdeljeno v pet con. Ta delitev ni vezana na administrativne ovire, ampak je namenjena le natančnim izračunom in predstavitvam potreb po energiji. Cone so prikazane na sliki in v preglednici 1.

the percentage of the number of inhabitants, except for those zones with a small number of inhabitants, where a minimum required sample of 50 households was adopted. The area of the Municipality of Rijeka was divided into five zones. These area divisions have no connection with administrative boundaries, but serve mainly for detailed and more accurate calculations and presentations of the energy requirements. The zones are shown in figure 1 and table 1.



Sl. 1. *Razporeditev con na Primorsko-goranskem območju*
Fig. 1. *Survey zones in the territory of Primorsko-goranska County*

1 REZULTATI ANALIZE

1.1 Splošna analiza

Število članov v gospodinjstvih je parameter, ki bistveno vpliva na porabo energije. Povprečno število članov gospodinjstev v Primorsko-goranskem okrožju je bilo 3,28. Slika 2 prikazuje povprečno število članov gospodinjstev v posameznih conah, slika 3 pa prikazuje porazdelitev gospodinjstev z različnim številom članov.

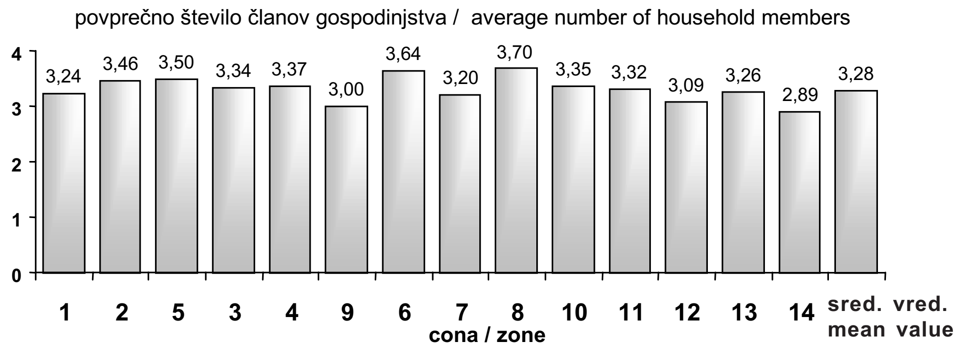
1 RESULT OF ANALYSIS

1.1 General analysis

The number of household members is one of the parameters that influences household energy consumption. The average number of household members for the whole survey sample in Primorsko-goranska County is 3.28. Figure 2 shows the average number of household members for the analyzed zones and figure 3 gives a breakdown of the different household members in the surveyed households.

Preglednica 1. *Seznam con*
Table 1. *List of survey zones*

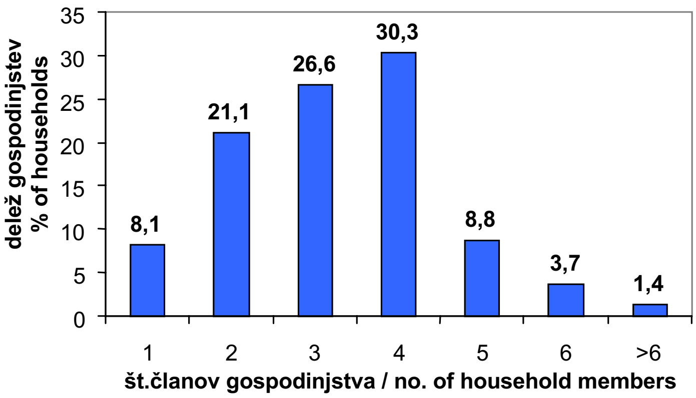
Cona Zone	opis description	št. prebivalcev no. of inhabitians	vključena gospodinjstva surveyed households
1	mestna središča Gorskega Kotarja urban centers of Gorski Kotar	7340	50
2	Gorski Kotar brez mestnih središč Gorski Kotar without urban centers	23205	142
3	turistična središča ob obali tourist centers on the coast	26524	166
4	obala brez turističnih središč coast without tourist centers	8483	53
5	obalno zaledje coastal hinterland	50524	313
6	turistične namestitve na obalah otokov tourist settlements on the coastal region of the islands	27716	173
7	druge namestitve na obalah otokov other settlements on the coastal region of the islands	4533	50
8	namestitve v zaledju otokov settlements in the hinterland of the islands	5154	50
9	Kostrena in Bakar Kostrena and Bakar	5576	50
10	Reka – pretežno družinske hiše brez plinovoda Rijeka – predominantly family houses without gas-pipe network	15176	94
11	Reka – pretežno družinske hiše s plinovodom Rijeka – predominantly family houses with gas-pipe network	4660	50
12	Reka – pretežno stanovanja brez plinovoda Rijeka – predominantly flats without gas-pipe network	114520	707
13	Reka – pretežno stanovanja s plinovodom Rijeka – predominantly flats with gas-pipe network	14490	90
14	Reka – stari del mesta s plinovodom Rijeka – older center with gas-pipe network	15229	95
	SKUPAJ ZA OBMOČJE TOTAL FOR COUNTY	323130	2083



Sl. 2. *Povprečno število članov gospodinjstev*
Fig. 2. *Average number of household members*

Uporaba različnih gospodinjskih naprav močno vpliva na energijsko porabo. Na sliki 4 je prikazana porazdelitev gospodinjskih naprav in lastništvo avtomobilov. Iz tega lahko vidimo, da ima 60 % gospodinjstev po en avtomobil, skoraj 13% gospodinjstev v okrožju pa dva ali več. Delež telefonskih priključkov znaša 93,5%, klimatske naprave pa uporablja le 1,8% gospodinjstev.

The use of different household devices strongly influences the household energy consumption. A breakdown of the use of household devices in the surveyed sample of households as well as the ownership of cars is shown in figure 4. It can be seen that 60% of households possess one car, but nearly 13% of households in the County have two or more cars. The number of household telephoneline-line connections is high, 93.5%; in contrast, air-conditioning devices are used in only 1.8 % of households.



Sl. 3. *Porazdelitev gospodinjstev glede na različno število članov gospodinjstev*
Fig. 3. *Number of members per households*

1.2 Analiza porabe energije

1.2.1 Celotna letna poraba končne energije v gospodinjstvih

Celotna letna poraba končne energije v gospodinjstvih v Primorsko-goranskem okrožju je približno 5,4 PJ. Celotna poraba končne energije po skupinah con je prikazana na sliki 5. Na isti sliki je prikazana tudi poraba končne energije glede na energijske vire. Lahko vidimo, da v območju Gorskega Kotarja in obalnega zaledja (cone 1, 2, 5) 61% celotne končne energije pridobijo z uporabo drv. V obalnih regijah pade ta odstotek na 38% na obali (cone 3, 4, 9) in na 27% na otokih (cone 6, 7, 8). V mestni občini Reka je glavni energijski vir elektrika (44%), sledijo drva (28%) in daljinsko ogrevanje (12%).

1.2.2 Poraba končne energije za ogrevanje

Na celotnem območju, z izjemo otokov, so glavni energijski vir ogrevanja drva, še posebno na območju Gorskege Kotarja in obalnega zaledja (cone 1, 2, 5), kjer znaša ta delež 75%, v obalnih regijah (cone 3, 4, 9) 61% in na otokih (cone 3, 4, 9) 44%. V mestni občini Reka znaša delež drv za ogrevanje 45%, sledijo elektrika (18%) in daljinsko ogrevanje (17%).

1.2.3 Poraba končne energije za pripravo tople sanitarne vode (TSV)

Največji delež porabe končne energije za pripravo tople sanitarne vode v gospodinjstvih zavzema elektrika, še posebej v obalnih regijah (cone 3, 4, 9), kjer znaša ta vrednost 91%, na otokih (cone 5, 6 in 8) 71%. V območju mestne občine Reka (cone 10-14) je delež električne energije nižji in znaša 67%, saj daljinsko ogrevanje zagotavlja

1.2. Analysis of energy consumption

1.2.1. Total annual energy consumption in households

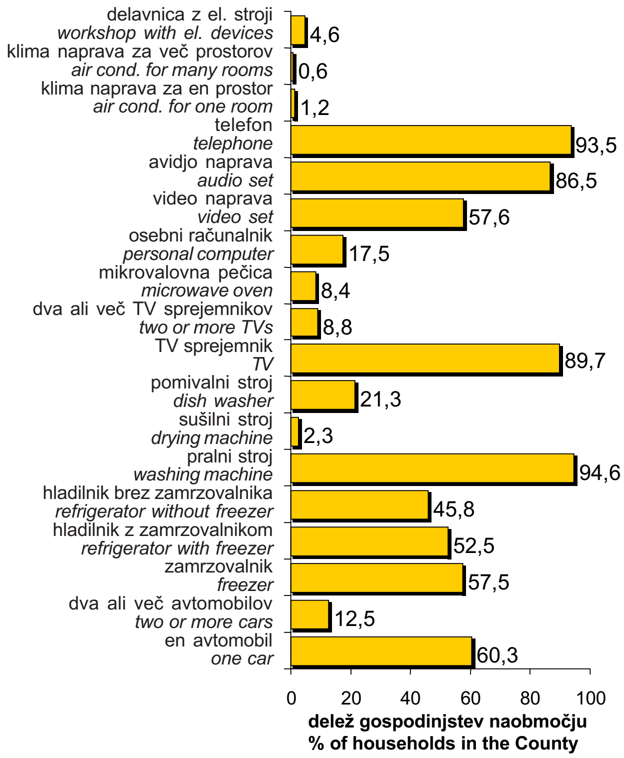
The total annual energy consumption of households in Primorsko-goranska County is about 5.4 PJ. The total energy consumption for every group of zones is shown in Figure 5. In addition, the total energy consumption in terms of energy sources has also been presented in the same figure. It can be seen that in the area of Gorski Kotar and the littoral hinterland (zones 1,2 and 5) 61% of the total energy is provided by wood fuel. In coastal regions the amount of wood fuel in the total energy consumption drops to 38% on the coast (zones 3,4 and 9) and 27% of the total energy consumption on the islands (zones 6, 7 and 8). In the Municipality of Rijeka electrical energy accounts for 44% of the total with wood fuel (28%) and district heating (12%) providing lesser amounts.

1.2.2. Final energy consumption for space heating

The whole area, except the islands, wood fuel occupies a major proportion of the total energy consumption for space heating, especially in the area of Gorski Kotar and the littoral hinterland (zones 1,2 and 5) with a share of 75%, on the coastal region (zones 3,4, and 9) 61% and on the islands (zones 3,4 and 9) 44%. In the Municipality of Rijeka the proportion of wood fuel in the total energy consumption for space heating is 45%, followed by electricity (18%), and district heating (17%).

1.2.3. Total energy consumption for sanitary hot water (SHW) heating

The largest part of the totall energy consumption for sanitary hot-water heating in households is allocated to electricity, especially in the coastal region (zones 3,4 and 9) where the proportion of electricity in the total energy consumption for SHW heating is 91%. On the islands (zones 5, 6, 8) electricity provides 71% of the total energy for SHW preparation. In the Municipal-



Sl. 4. *Uporaba različnih gospodinjskih naprav in lastništvo avtomobilov*
Fig. 4. *Use of different household devices and car ownership*

17% energije. Največje deleže v porabi končne energije za pripravo tople sanitarne vode v regijah Gorskega Kotarja in obalnega zaledja (cone 1, 2 in 5) zavzemajo drva (53%) in električna energija (39%).

1.2.4 Poraba končne energije za kuhanje

Največji delež porabe končne energije za kuhanje v gospodinjstvih v obalnih regijah (cone 3, 4 in 9) in na otokih (cone 6, 7, 8) pomeni utekočinjeni naftni plin (UNP). V gospodinjstvih Gorskega Kotarja in obalnega zaledja pa imajo glavno vlogo drva (58%). V mestni občini Reka pa zavzema električna energija 37%, drva 27%, UNP 20% ter plin iz plinovoda 16%.

1.2.5 Struktura porabe končne energije

Največji del celotne porabe končne energije pridobijo iz drv (40%) in električne energije (35%). Sledijo kurilno olje 15%, daljinsko ogrevanje 5%, UNP 4% in plin iz omrežja 1,5%. Struktura porabe končne energije v gospodinjstvih glede na energijske vire in uporabo je prikazana na sliki 6.

Največji delež porabe končne energije v gospodinjstvih pomeni ogrevanje (59%), približno 13% priprava tople sanitarne vode, 11% kuhanje in 17% preostalo.

ity of Rijeka (zones 10-14) this proportion is lower and corresponds to 67%, while district heating provides 17% of the energy. Energy for SHW heating in the regions of Gorski Kotar and the littoral hinterland (zones 1,2,5) is provided by wood fuel (53%) and electricity (39%).

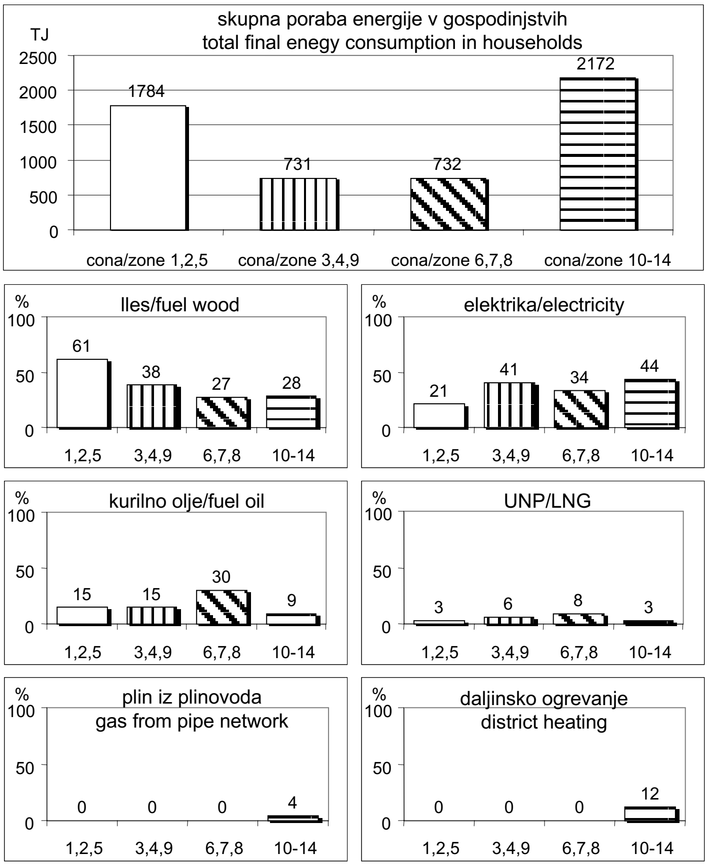
1.2.4. Total energy consumption for cooking in households

The largest proportion of energy for cooking in households situated in the coastal regions (zones 3,4,9) and on the islands (zones 6, 7, 8) comes form Liquified Naphta Gas (LNG). In households located in Gorski Kotar and the coastal hinterland, 58% of the energy for cooking is provided by wood fuel. In the Municipality of Rijeka the energy requirements for cooking are electricity (37%), wood fuel (27%), LNG (20%) and gas from a piped network (16%).

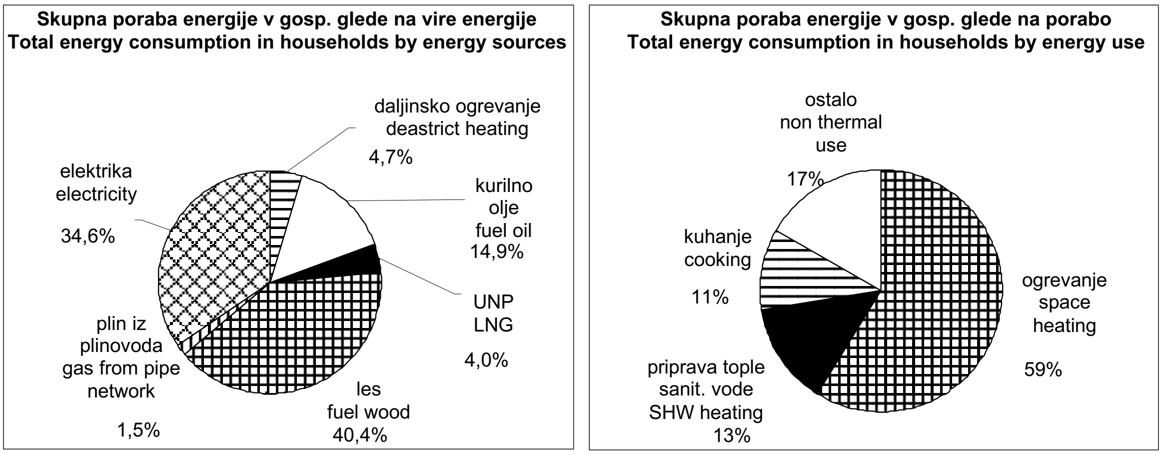
1.2.5. Energy consumption structure

The overall energy consumed in Primorsko-goranska County comes from wood fuel (40%) and electricity (35%). Additional energy is supplied by fuel oil with a proportion of about 15%, district heating 5%, LNG 4% and a piped-gas network with 1.5%. A breakdown of the total energy consumption for households in terms of energy sources and energy use is shown in figure 6.

The largest part of the total energy consumption in households is used for space heating with a proportion of 59%. About 17% of the energy requirements are used for non-thermal needs, 13% for sanitary hot-water preparation and 11% for cooking.



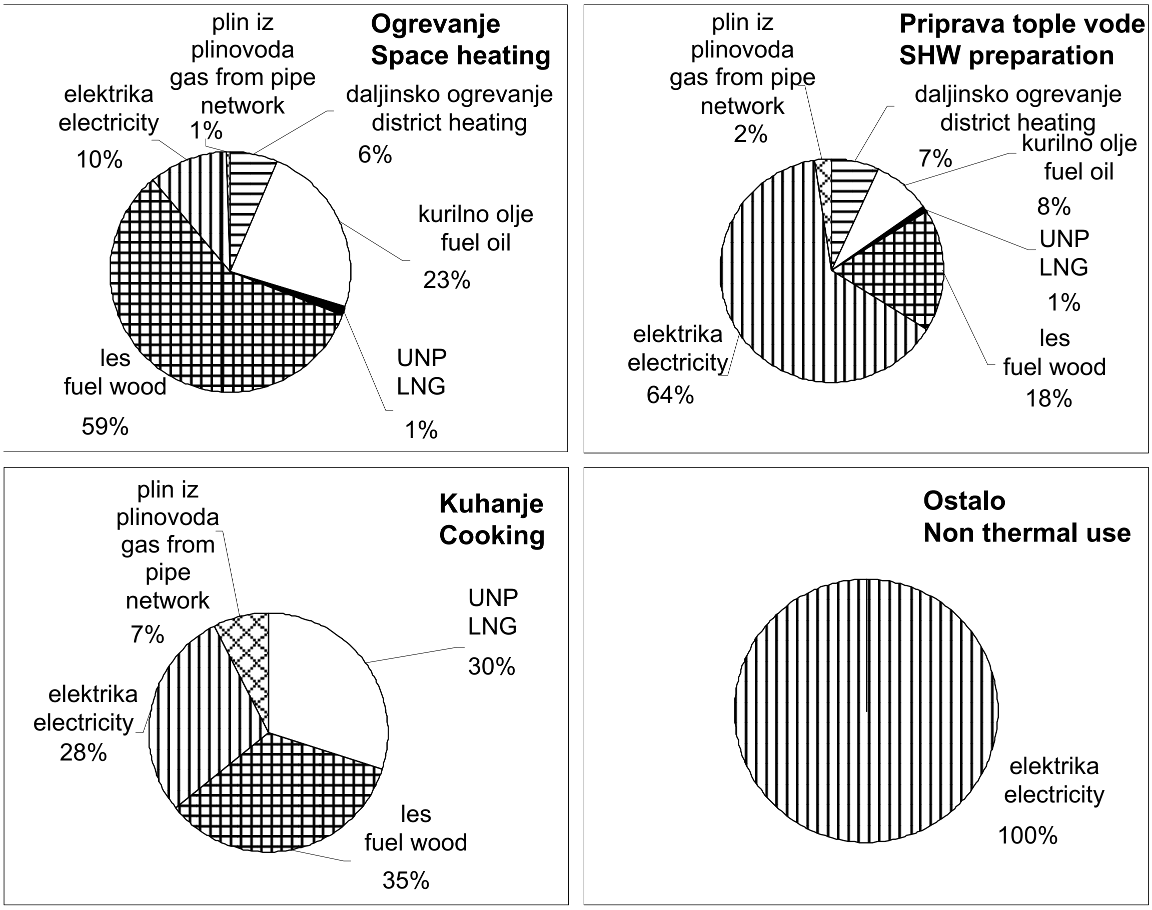
Sl. 5. *Celotna poraba končne energije v gospodinjstvih glede na različne energijske vire*
Fig. 5. *Total energy consumption in households in terms of different energy sources*



Sl. 6. *Porazdelitev porabe končne energije glede na energijske vire in glede na uporabo energije*
Fig. 6. *Breakdown of the total energy consumption in households by energy sources and by energy use*

Na sliki 7 je prikazana porazdelitev energijskih virov za vsako zgoraj omenjeno področje. Vidimo, da so drva glavni energijski vir za ogrevanje, temu sledita kurilno olje in elektrika. Za pripravo tople sanitarne vode izstopajo električna energija in drva. Kot energijski vir za kuhanje uporabljajo drva, UNP, električno energijo in plin iz omrežja.

The structure of energy sources for each segment of energy use is shown in figure 7. It is clear that wood fuel represents a major energy source for space heating in households, this is followed by fuel oil and electricity. The energy for SHW preparation is mainly provided by electricity and wood fuel. Wood fuel, LNG, electricity and piped gas are used as the main energy sources for household cooking.



Sl. 7. *Porazdelitev energijskih virov glede na uporabo energije*
Fig. 7. *Structure of energy sources for each segment of energy use*

2 SKLEP

Porazdelitev porabe končne energije v gospodinjstvih Primorsko-goranskega območja kaže, da je samo 80 TJ ali 1,5% energije porabljene iz plinovoda. Podobna analiza za območje mestne občine Reka kaže, da ta energijski vir pokriva le 3,7% celotnih potreb po končni energiji gospodinjstev. Rezultati analiz porabe končne energije gospodinjstev in izračuni porab energije v industriji in javnih sektorjih so osnova za predvidevanja potreb po energiji v okrožju. Na podlagi načrtovanj potreb po energiji in ocenitvi stroškov za izvedbo projekta lahko določimo območja, primerna za izvedbo plinifikacije. Rezultati raziskav so temelj za projekt plinifikacije regije.

2 CONCLUSION

The structure of energy consumption for households situated in the region of Primorsko-goranska County shows that only 80 TJ or about 1.5% of energy is provided from a piped-gas network. A similar analysis for the area of the Municipality of Rijeka shows that this energy source provides only 3.7% of the total energy needs of households. The results of the household energy consumption analysis and the calculation of energy consumption in industry and service sectors are the basis for a prediction of the energy requirements of the County. Areas where a new piped-gas network will be worthwhile can be determined from energy-demand predictions and the estimated capital cost for a piped-gas network using a feasibility analysis. The results of the research are a basis for the project to introduce gas to the region.

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Poraba energije v gospodinjstvih

Energy Use in Households

Jurij Modic

V Sloveniji je približno 660.000 gospodinjstev. Z uporabo statističnih podatkov (dobljenih v okviru mednarodnega projekta SACHA 2/Energy 2000) smo analizirali električne gospodinjske aparate in njihovo porabo energije v slovenskih gospodinjstvih. Emisije CO_2 in SO_2 so izračunane na podlagi znanih energijskih virov (premog, hidroelektrarne, jedrska elektrarna) in porabe. Zamenjava manj učinkovitih električnih naprav z učinkovitejšimi se kaže pri zmanjšanju porabe električne energije, manj je tudi konic obremenitev in emisij iz elektrarn.

(Ključne besede: gospodinjstva, poraba energije, aparati gospodinjski, učinkovitost energijska)

There are about 660,000 households in Slovenia. Based on questionnaire data (as part of the SACHA 2/Energy 2000 international project) we have analysed the electrical appliances in Slovenian households and their energy consumption. The CO_2 and SO_2 emissions were calculated on the basis of known electricity consumption and known electricity sources (coal, hydro and nuclear power plants). The replacement of less efficient electrical appliances is reflected in a reduced electricity consumption, reduced peak loads and a reduction in the emissions from power plants.

(Keywords: households, energy consumption, household appliances, energy efficiency)

0 OSNOVE IN PREDSTAVITEV

Od leta 1995 so Evropska komisija, Program EU SAVE in Ekonomska komisija ZN za Evropo (Projekt energijske učinkovitosti 2000) sponzorirale t. i. projekt SACHA glede domače in terciarne električne energije ter porabe v srednjih in vzhodnoevropskih državah. SACHA je akronim naziva prvega projekta: "***S****tate of the* ***A****rt of* ***C****ooling* ***H****ousehold* ***A****ppliances - Stanje tehnike gospodinjskih hladilnih naprav - Standardi, trg in tehnologija v srednje in vzhodnoevropskih deželah za uporabo programov energetske učnkovitosti v državah članicah srednje in vzhodne Evrope*", ki je bil končan oktobra 1997 (trajal je 20 mesecev). Decembra 1998 so pričeli s projektom SACHA-2[1], v juniju tega leta pa je bil financiran tudi SACHA-2.1[2].

Glavni namen tega projekta sta bili analiza in interpretacija hladilnih gospodinjskih naprav (HGN) v štirih vzhodnoevropskih državah (Belorusija, Bolgarija, Madžarska in Ukrajina), da bi: i) povečali dosedanje znanje in ii) napisali scenarije za izboljšanje glede na energijsko

0 BACKGROUND AND INTRODUCTION

Since 1995 the European Commission in the form of the EU SAVE Programme and the Economic Commission for Europe of the UN (Energy Efficiency 2000 Project) have jointly sponsored the so-called "SACHA" projects in Central and Eastern European Countries on domestic and tertiary electrical end uses. SACHA is the acronym from the title of the first project: "***S****tate of the* ***A****rt of* ***C****ooling* ***H****ousehold* ***A****ppliances* ***S****tandards, Market and Technology in Central and Eastern European Countries for Energy Efficiency Programmes Implementation in ECE Member State*", which was completed in October 1997 (20 months duration). In December 1998 the SACHA-2[1] project started, and in June of this year the SACHA-2.1[2] project was also financed.

The main objective of the first project was to analyse and interpret the situation with respect to **C**ooling **H**ousehold **A**ppliances (CHA) in four ECE Countries (Belarus, Bulgaria, Hungary and Ukraine), in order to: i) increase current knowledge, and ii) identify possible scenarios for improvement with regard to the issues of energy efficiency and environmental friendliness, and there-učinkovitost in prijaznost okolju in nato iii) predlagali pristojnim oblastem politiko in ukrepe v elektrogospodarstvu. Glede na velik uspeh prve naloge, so pri projektih SACHA-2 in 2.1 povečali število proučevanih držav na sedem, dodali so Češko republiko, Romunijo in Slovenijo. Kot dodatni sektorji in izdelki pa so bili vključeni še pralni gospodinjski aparati (PGA) in domača/terciarna osvetljava (DTO).

Projekt SACHA-2 in dodatni del za razsvetljavo SACHA 2.1 uporabljata in posodabljata metode, ki so bile določene in učinkovite pri prvem projektu, da bi s tem povečali znanje na področju gospodinjskih naprav/osvetljave v državah srednje in vzhodne Evrope.

fore iii) identify and propose to national authorities possible policies and measures in the domestic electrical end-use sector. As a result of the great success of the first exercise, the SACHA-2 and 2.1 projects increased the number of investigated countries to seven, with Czech Republic, Romania and Slovenia joining the Working Group, and **W**ashing **H**ousehold **A**ppliances (WHA) and **D**omestic/**T**ertiary **L**ighting (DTL) added as sectors and products to be analysed.

The SACHA-2 project and the additional part relating to lighting in the SACHA 2-1 project make use of and update the methodology defined and validated in the first project to increase knowledge in the field of household appliances/lighting Central and Eastern European Countries.

1 NAMEŠČENE NAPRAVE – GOSPODINJSKI APARATI

1 PROFILE OF INSTALLED HOUSEHOLD APPLIANCES

1.1 Hladilne gospodinjske naprave

Funkcionalno delovanje se povečuje z zmanjševanjem temperature v vsakem prostoru. Temperatura in ustrezna zmogljivost so podane v mednarodnih/evropskih standardih.

V Belorusiji, Romuniji, Sloveniji in Ukrajini imajo skoraj vsi nameščeni modeli zamrzovalnik, sledijo Madžarska z 84% takih modelov, Bolgarija in Republika Češka s približno 70% (69,4% v Republiki Češki in 67,5% v Bolgariji).

1.1 Cooling Household Appliances

In general, the performance increases with a decrease in the temperature reached in each type of compartment. The temperature and corresponding performance are set by international/European standards for most of the compartments.

In Belarus, Romania, Slovenia and Ukraine almost all installed models have a freezer compartment, followed by Hungary with 84% and then by Bulgaria and Czech Republic with around 70% (69.4% in Czech Republic and 67.5% in Bulgaria).

1.1.1 Porazdelitev prostornine hladilnih gospodinjskih naprav

V Belorusiji ima več ko 70% nameščenih hladilnikov prostornino med 200 in 300 litri ali več,

1.1.1 Cooling Household Appliances Volume Distribution

In Belarus, more than 70% of the installed refrigerators have a volume between 200 and 300 litres, while small

Preglednica 1. *Primerjava nameščenih hladilnih naprav v srednje in vzhodnoevropskih državah*
Table 1. *Estimated compartment composition for installed refrigerators in ECE countries*

Nameščene naprave Installed appliances	Belorusija Belarus		Bolgarija Bulgaria		Češka Czech Rep.		Madžarska Hungary		Romunija Romania		***Slovenija Slovenia***		Ukrajina ('95) Ukraine ('95)	
	Št. No	%	Št. No	%	Št. No	%	Št. No	%	Št. No	%	*Št. No*	*%*	Št. No	%
enote z zamrzovalnikom units with freezer compart.	1002	**100**	672	**67,5**	705	**69,4**	818	**84,1**	924	**99,4**	***973***	***98,6***	**911**	**99,9**
enote brez zamrzovalnika units without freezer compart.	0	0	321	32,5	311	30,6	155	15,9	6	0,6	***14***	***1,4***	1	0,1
skupaj total	1002		988		1016		973		930		***987***		912	
baza (lastniki hladilnikov) *base (RF owners)*	*1002*		*996*	99,2	*1016*		*1007*	(96,6)	*930*		***989***	***(99,8)***	*915*	(99,7)

[1] Projekt SACHA-2: Stanje tehnike gospodinjskih hladilnih in drugih večjih naprav - Standardi, trg in tehnologija v srednje in vzhodnoevropskih deželah za izboljšanje izkoristka v državah članicah ECE.

[1] SACHA-2 project: "State of the Art of Cooling Household and Other Major Appliances Standards, Market and Technology in Central and Eastern European Countries for Energy Efficiency Improvement in ECE Member States".

[2] Projekt SACHA2.1: Stanje tehnike osvetljevalnih sistemov in gradnikov - Standardi, trg in tehnologija v srednje in vzhodnoevropskih deželah za izboljšanje izkoristka v državah članicah ECE.

[2] SACHA-2.1 project: "State of the Art of Lighting Systems and Components_Standards, Market and Technology in Central and Eastern European Countries for Energy Efficiency Improvement in ECE Member States".

majhnih hladilnikov tu ni. V Bolgariji, če izločimo majhne in velike enote, se giblje 25% prostornin hladilnikom med 250 in 300 litri, manjše število pa je takih med 150 in 200 litri. Republika Češka in Madžarska imata zelo podobno porazdelitev prostornine, 100 do 250 in 150 do 200. Tudi v Romuniji imajo modeli prostornine med 100 in 250 litri, največ pa jih je med 200 in 250 litri (kar 43%, medtem ko je takih na Madžarskem le 30%); naprav s prostornino manjšo od 100 litrov in večjo od 250 je skupno manj ko 5%. V Sloveniji je približno 90% naprav manjših od 200 litrov, 40% jih je med 100 in 150 litri. V Ukrajini ne obstajajo hladilniki do 100 litrov, tam je kar 75% vseh med 150 in 250 litri.

1.1.2 Značilnosti zamrzovalnih predelov

V vseh državah razen Češke republike so zamrzovalniki z dvema zvezdicama najbolj pogosti, razlikujejo se glede odstotka, od 73% v Romuniji do 32% v Bolgariji (leto 1995). Drugi najpogostejši zamrzovalnik s tremi zvezdicami je v Belorusiji (32,4% v 1995, glede odstotkov zelo blizu zamrzovalniku z dvema zvezdicama), Madžarski (33,3%, v istem letu), Romuniji (12,4%) in Sloveniji (37,3%, tudi glede odstotkov zelo blizu zamrzovalniku z dvema zvezdicama). Zamrzovalnik brez zvezdic je najpogostejši v Bolgariji (24,3%, v letu 1995), z eno zvezdico v Ukrajini (23,6%, leta 1995), in s štirimi zvezdicami v Republiki Češki (32,2%). V Bolgariji je bilo leta 1995 okoli 22% zamrzovalnikov s štirimi zvezdicami.

V Bolgariji in Češki republiki imajo najbolj enakomerno porazdelitev prostornin po kategorijah, tam so zamrzovalniki do 75 litrov

appliances are absent. In Bulgaria, excluding very small and large units, volumes are more evenly distributed, with 250 to 300 litre units corresponding to 25% of the stock with fewer units in the range 150 to 200 litres. Czech Republic and Hungary show a very similar volume distribution, with most of the appliances distributed in the range 100 to 250 litres, with a peak at 150 to 200 litres which is slightly higher Hungary. For Romania most of the installed models also lie in the range 100 to 250 litres, with a large peak (about 43%, against about 30% of Hungary) at 200 to 250 litres; appliances with a volume lower than 100 litres and larger than 250 account for less than 5%. In Slovenia about 90% of the installed units are less than 200 litres, with 40% between 100 and 150 litres. In Ukraine no units of less than 100 litres exist, and about 75% are between 150 and 250 litres.

1.1.2 Freezer-Compartment Characteristics

In all countries except Czech Republic two-star freezers are the majority, but with different percentages, ranging from about 73% in Romania down to about 32% in Bulgaria in 1995. The next most common types of freezer are the three-star in Belarus (32.4% in 1995, very close in percentage to the two-star), Hungary (33.3% in the same year), Romania (12.4%) and Slovenia (37.3%, similar to the number of two-star freezers, the 0-star in Bulgaria (24.3% in 1995), the one-star in Ukraine (23.6% in 1995), and the four-star in Czech Republic (32.2%). In Bulgaria four-star freezers were also around 22% in 1995.

Bulgaria and Czech Republic show the most even distribution of models in volume categories, with compartments up to 75 litres more common than larger volumes. In Hungary and Slovenia around 70% of the installed units have a freezer compartment up to 25 litres, and this percentage increases to around 80% in Roma-

Preglednica 2. *Položaj zamrzovalnikov s štirimi zvezdicami v kombinaciji hladilnik/zamrzovalnik v srednje in vzhodnoevropskih državah (leta 1995 in 1997)*
Table 2. *Position of the four-star freezer for installed fridge/freezers in ECE (1995 and 1997)*

Dežela Country	Zgoraj Top Št. No.	 %	Spodaj Bottom Št. No.	 %	Skupaj Tot. Št. No.
Belorusija ('95) Belarus ('95)	75	72,1	29	27,9	104
Bolgarija ('95) Bulgaria ('95)	102	68,9	46	31,1	148
Češka republika Czech Republic	49	34,3	94	65,7	143
Madžarska ('95) Hungary ('95)	73	57,9	53	42,1	126
Romunija Romania	52	89,7	6	10,3	58
Slovenija Slovenia	***102***	***74,6***	***33***	***24,4***	***135***
Ukrajina ('95) Ukraine ('95)	15	83,3	3	16,7	18

najbolj pogosti. Na Madžarskem in v Sloveniji ima 70% nameščenih enot zamrzovalnikov do 25 litrov, v Romuniji je teh 80%. V Belorusiji so najbolj pogosti zamrzovalniki s prostornino med 25 in 50 litri, medtem ko v Ukrajini prevladujejo taki do 25 litrov.

Za Češko republiko, Romunijo in Slovenijo so raziskovali tudi nižjo kategorijo. Zasledili so enak trend; 86,1% in 92,8% zamrzovalnikov s tremi zvezdicami v Romuniji in Sloveniji in le 47,3% v Češki Republiki.

1.1.3 Druge značilnosti hladilnikov in hladilnih zamrzovalnikov

Druge značilnosti hladilnikov in hladilnih zamrzovalnikov, tj. število zunanjih vrat in termostatov, prosto stoječi ali vgradni, debelina izolacije ter odtajevalni sistem, se razlikujejo po državah.

Vse naprave imajo ena glavna ali dvoja vrata, po tri ali štiri imajo le zelo redki. Naprav z enimi vrati le od 60% pa do več ko 93%; le v Češki republiki ima malo manj ko 40% hladilnikov dvoja vrata. V šestih od sedmih držav ima 90% ali več naprav po en termostat, dva termostata sta bolj običajna na Češkem (20,2%). Vgradni aparati predstavljajo več ko 25% vseh nameščenih v Sloveniji, 30% v Italiji in 8,6% v Češki republiki. V vseh drugih državah imajo več ko 98% stoječih naprav. Za Belorusijo, Bolgarijo, Madžarsko in Ukrajino je bila v okviru projekta SACHA-1 kot možna izolacija uporabljena mineralna volna in je sedaj prikazana kot ″drugi″ tip izolacije.

Zamrzovalniki so bolj pokončnega (navpičnega) tipa v primerjavi z zabojastim (vodoravnim) v vseh državah, razen v Sloveniji, kjer je takih približno dve tretjini; na Madžarskem je število pokončnih in zabojastih skoraj enako (pokončnih je malo več, tabela 2.3). V zadnjem stolpcu so prikazani odstotki dobljenih odgovorov.

Skoraj vse enote (najmanj več ko 94%) so stoječe. Izolacija ima normalno debelino v nekaj več kot 40% naprav, pri približno polovici v Belorusiji in Ukrajini, približno 70% na Madžarskem in v Romuniji ter skoraj pri vseh napravah v Češki Republiki (85%) in Sloveniji (92,1%). Nadpovprečno izoliranih naprav je od 20 do 30% v vseh državah, razen v Češki Republiki in Sloveniji, kjer jih je 9,7% in 4,5%. Pri prvem projektu SACHA je bila v raziskave vključena tudi izolacija z mineralno volno, ki je sedaj vključena v ″druge tipe″ izolacij.

Ročni sistem odtajanja je najpogostejši v Češki republiki, na Madžarskem, v Romuniji, Sloveniji in Ukrajini od 66,7% do 94,1%; le v Belorusiji je 70,6% naprav avtomatsko odtaljivih,

nia. In Belarus and Ukraine most of the units belong to the first two volume categories, but in Belarus compartments from 25 to 50 litres are the majority, while in Ukraina freezers up to 25 litres are more common.

For Czech Republic, Romania and Slovenia, the position of the freezer compartments with a lower star rating was also investigated. The same trend was detected, with 86.1% and 92.8% of the three-star freezer compartments on top in Romania and Slovenia, respectively, but only 47.3% in Czech Republic, where the majority of the freezers were again located at the bottom of the appliances.

1.1.3 Other refrigerator and fridge-freezer characteristics

Other features of installed refrigerators and fridge-freezers, such as the number of external doors and thermostats, free-standing or built-in design, insulation thickness and defrosting system vary from country to country.

Almost all appliances have one or occassionally two doors; three- and four-door models are very rare. Single-door units account for 60% to 93% of the total; only in Czech Republic do slightly less than 40% of the refrigerators have two doors. In six countries out of seven 90% or more of the appliances have one thermostat, two-thermostat models are again more common in Czech republic (20.2%). Built-in units represent more than 25% of the installed stock in Slovenia, very close to 30% in Italy, and 8.6% in Czech Republic. In all other countries free-standing models account for more than 98%. For Belarus, Bulgaria, Hungary and Ukraine, the alternative of mineral wool insulation was asked for in the framework of SACHA-1 project, and it is now indicated as “other” types of insulation.

Installed freezers tend to be of the upright (vertical) type, rather than chest (horizontal) models in all countries but Slovenia, where chest freezers account for about two thirds of the installed stock; in Hungary the distribution between vertical and horizontal units is almost even, with the upright type being slightly more common (Table 2.3). In the last column the percentage of answers from freezer owners is shown when less than 100% was achieved.

Almost all units (more than 94%) are “free-standing”. Insulation has a normal thickness in slightly more than 40% of the appliances in Bulgaria, in about half in Belarus and Ukraine, around 70% in Hungary and Romania and almost all appliances in Czech Republic (85%) and Slovenia (92,1%). Super-insulated models are about 20-30% of the stock in all countries except for Czech Republic and Slovenia, where they account for 9.7% and 4.5%, respectively. Some mineral wool insulation was found in appliances from countries in the first SACHA project. This is now included in “other type” of insulation.

The defrosting system is mostly manual in Czech Republic, Hungary, Romania, Slovenia and Ukraine with the percentage going from 66.7% in Ukraine to 94.1% in Romania; only in Belarus are 70.6% of the appliances

Preglednica 3. *Tipi nameščenih zamrzovalnikov v državah srednje in vzhodne Evrope v letih 1995 in 1997*
Table 3. *Installed freezer type in ECE countries in 1995 and 1997*

Dežela Country	Pokončni Upright		Zabojasti Chest		Skupaj Tot.
	Št. No.	%	Št. No.	%	Št. No.
Belorusija ('95) Belarus ('95)	28	80,0	7	20,0	35
Bolgarija ('95) Bulgaria ('95)	185	66,5	93	33,5	278
Češka Republika Czech Republic	299	72,2	115	27,8	414
Madžarska ('95) Hungary ('95)	356	54,0	303	46,0	659
Romunija Romania	343	95,5	16	4,5	359
Slovenija Slovenia	***234***	***33,1***	***474***	***66,9***	***708***
Ukrajina ('95) Ukraine ('95)	9	90,0	1	10,0	10

medtem ko je v Bolgariji 40% avtomatskega in 40% ročnega. Zamrzovalnikov, ki jih ni treba odtajevati, ni ali pa jih je le majhen odstotek, izjema je tu Bolgarija, kjer imajo 12% takih primerov.

automatically defrostable. In Bulgaria, automatic and manual defrosting account for about 40% each. No-frost freezers are either absent or represent just a few percent in all countries, the exception being Bulgaria where about 12% of the units are of the No-frost type.

1.2 Pralni stroji

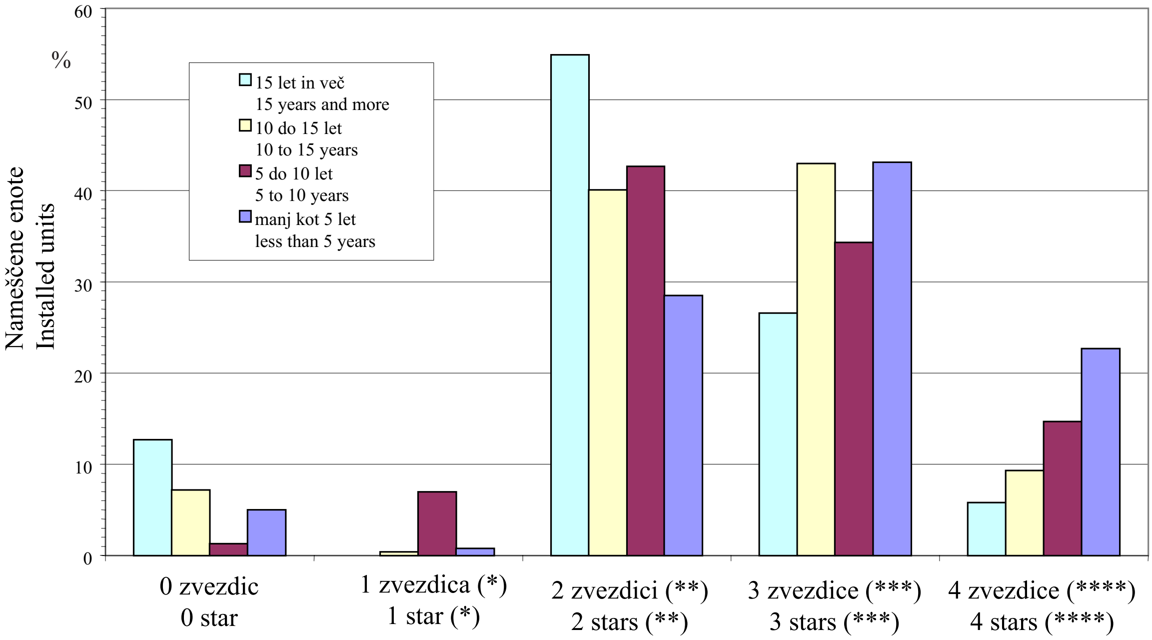
1.2 Washing Machines

1.2.1 Splošne značilnosti pralnih strojev

1.2.1 General characteristics of washing machines

V različnih državah se odstotek posameznega tipa (avtomatski, polavtomatski ali ne-avtomatski) razlikuje. Neavtomatski modeli prevladujejo v Belorusiji, Romuniji in Ukrajini

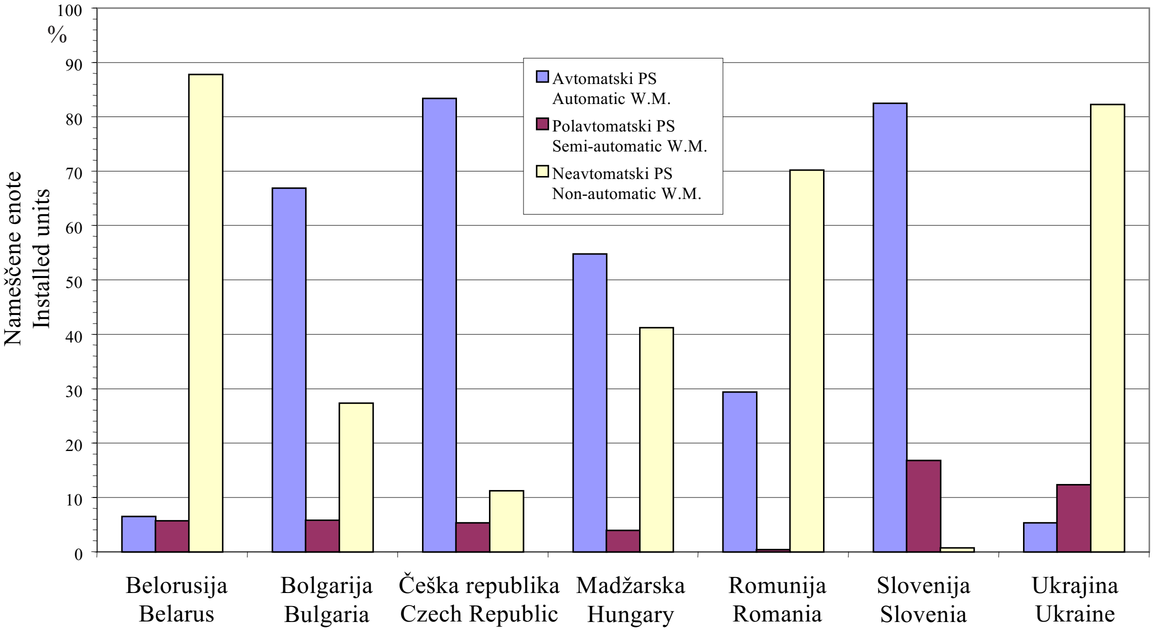
The percentage of each type (automatic, semi-automatic or non-automatic) in the different countries varies. Non-automatic models are the great majority in Belarus, Romania and Ukraine (87.8%, 70.2% and 82.3%



Sl. 1. *Nameščeni hladilniki in spremembe prostornin z leti (Slovenija)*
Fig. 1. *Installated refrigerators and volume modification with age (Slovenia)*

(87,3%, 70,2%, 82,3%) in jih praktično ne najdemo v Sloveniji (manj kot 1%), medtem ko avtomatski prevladujejo v Bolgariji, Češki republiki in Sloveniji (66,9%, 83,4% in 82,5). V Belorusiji in Ukrajini jih je približno 5-6%. Na Madžarskem pa je: avtomatskih je približno 55%, neavtomatskih pa 41%. Primerjava med državami je prikazana na sliki 2.

respectively), and practically absent in Slovenia (less than 1%), while automatic appliances are the majority in Bulgaria, Czech Republic and Slovenia (66.9%, 83.4% and 82.5% respectively) and around 5-6% in Belarus and Ukraine. Hungary is in an intermediate position, with automatic and non-automatic models accounting for about 55% and 41%, respectively. A comparison among countries is shown in Figure 2.



Sl. 2. *Tipi nameščenih pralnih strojev v državah srednje in vzhodne Evrope*
Fig. 2. *Installed washing machines type in ECE countries*

Z razliko od HGN imajo domači pralni stroji le pet možnih nominalnih obremenitev prostornine. Največja količina perila, ki ga operemo v pralnem stroju, je lahko 3 kg ali manj, 4,5 kg, 5 kg in 7 kg. Obremenitev avtomatskih pralnih strojev v Evropski skupnosti je med 4,5 in 5 kg, manj običajne so vrednosti 3 kg ali več kot 5 kg. Medtem pa polavtomatske in neavtomatske modele uporabljajo le redko in le za določene namene in njihova prostornina znaša 3 kg ali manj.

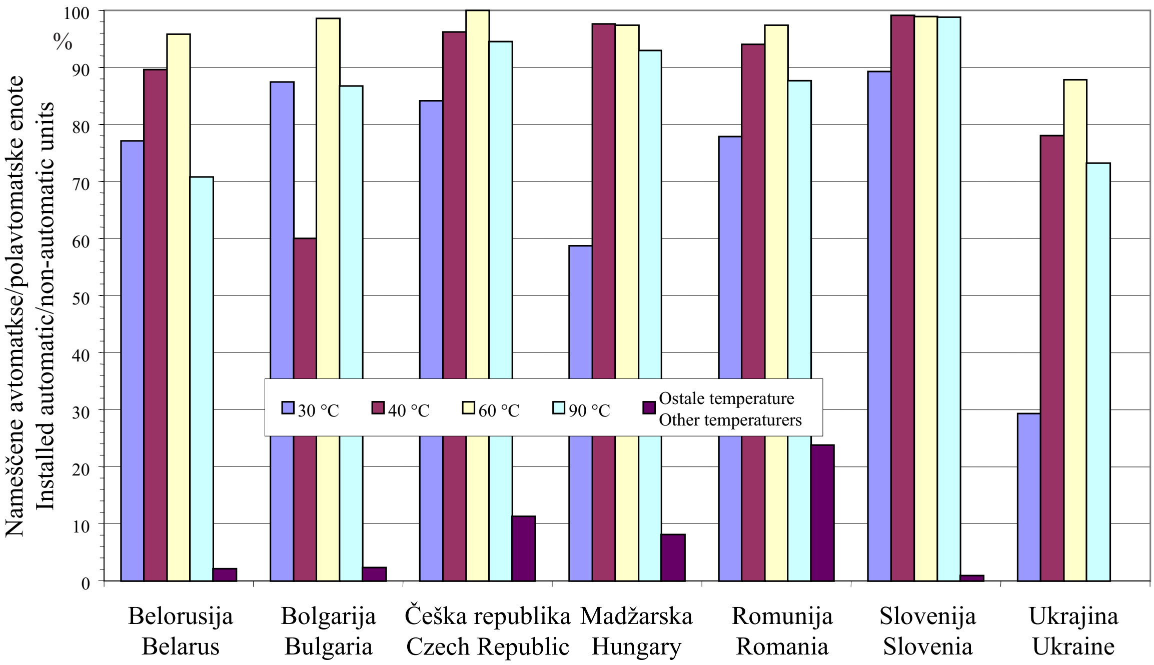
Pralnih strojev, katerih obremenitev znaša 5 kg, je manj kot 5% v Romuniji in Ukrajini, približno 10% v Češki republiki, približno 12 do 13% v Belorusiji, Bolgariji in na Madžarskem in 39% v Sloveniji. Več je pralnih strojev z nominalno obremenitvijo 7 ali več kg.

Naprave, ki imajo odprtino za vlaganje perila s čelne strani, prevladujejo v Bolgariji in Sloveniji. Medtem ko prevladujejo v Belorusiji, na Madžarskem, v Romuniji in Ukrajini naprave, ki imajo odprtino na vrhu. V Češki republiki uporabljajo oba tipa. Najpomembnejša tehnična značilnost je program pranja (temperatura in vrsta tkanine), ki ga ponuja posamezen model in so predstavljeni na sliki 3.

Unlike CHA, domestic washing machines present only five possible nominal loading capacities, i.e. the maximum amount of laundry that can be washed together in a washing cycle. These loading capacities are 3 kg or less, 4.5 kg, 5 kg and 7 kg. In the European Union, automatic washing machines are mostly 4.5 kg and 5 kg, with 3 kg and more than 5 kg much less common. Semi-automatic and non-automatic models are rare and used only for specific applications, their loading capacities are 3kg or less.

Five kg load washing machines account for less than 5% in Romania and Ukraine, around 10% in Czech republic, around 12 to 13% Belarus, Bulgaria and Hungary and around 39% in Slovenia. Larger washing machines, with a nominal load of 7 kg or more are rare.

Front-loading appliances are the majority in Bulgaria and Slovenia, while top-loading machines are more common is in Belarus, Hungary, Romania and Ukraine. Czech Republic is in an intermediate situation with front-loading and top-loading machines accounting for about half of the installed stock, with the former type of washing machine being slightly more common. The most important technical characteristic is the washing programme (temperature and textile to be washed) offered by each model, as presented in Figure 3.



Sl. 3. *Temperature pranja nameščenih pralnih strojev v državah srednje in vzhodne Evrope (1997)*
Fig. 3. *Washing cycle temperatures for installed automatic machines in ECE countries (1997)*

2 EMISIJE CO_2

Slovenska gospodinjstva potrebujejo za HGN in PGA približno 25% celotne energijske porabe Slovenije, kar pomeni 2670 GWh v enem letu.

Iz termoelektrarn pridobijo 33% oz. 885 GWh. Za tri različne vrste premoga so izračunali emisije CO_2. Izračuni so pokazali, da slovenska gospodinjstva za HGN in PGA ″proizvedejo″ 890 Mt CO_2 na leto.

2 CO_2 EMISSIONS

Slovenian households account for about 25% of the Slovenian electricity consumption, which means 2670 GWh in one year.

The rate of thermo power plants is 33%, or 885 GWh. For 3 concrete kinds of Slovenian coals we calculated their CO_2 production. So the CO_2 pollution for CHA and WHA in Slovenian households is 890 Mt in one year.

3 LITERATURA
3 REFERENCES

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