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A CASE STUDY OF EXERGY ANALYSIS OF WASTE HEAT RECOVERY IN REFRIGERATION SYSTEM

ANALIZA EKSERGIJSKIH TOKOV V HLADILNEM SISTEMU Z IZKORIŠČANJEM ODPADNE TOPLOTE

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Keywords: exergy analysis, refrigeration system, waste heat recovery

Abstract

From an energy perspective, refrigeration systems employ a wasteful process; nevertheless, the food industry depends on refrigeration systems. To improve the efficiency of this process, a refrigeration system can be combined with a heating system, by using the waste heat from the condenser of the refrigeration system in the heating system. A case study of the application of a waste heat recovery system is considered in this paper. The conserved energy for three years is calculated, based on the literature, i.e. practical engineering articles. The numbers given are compared with the case study. The economic analysis reveals that the investment in an advanced refrigeration system is returned over a very short time. Two system models are discussed: a refrigeration system with no alternation and a refrigeration system that applies the recovery of waste energy. Exergy analysis has been developed for both models. The analysis shows an increase in the exergy efficiency of the advanced refrigeration system by 2%.

Povzetek

Z vidika porabe energije je hladilni sistem zelo potraten. Industrija hrane je odvisna od hladilnih sistemov. Proces hlajenja lahko naredimo bolj učinkovit tako, da izkoriščamo odpadno kondenzator-

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sko toploto. Opazovali smo konkreten primer na katerem smo sistem izkoriščanja odpadne toplote inštalirali. Izračunali smo izkoriščeno odpadno toploto v zadnjih treh letih delovanja sistema. Enačbe za preračun izrabljene odpadne toplote smo našli v starejši literaturi. Ekonomska analiza pokaže, da se začetna investicija povrne v zelo kratkem času. Z eksergijsko analizo sistema brez izkoriščanja odpadne toplote in sistema z izkoriščanjem odpadne toplote smo ugotovili, da ima slednji za 2% boljši eksergijski izkoristek.

1 INTRODUCTION

Refrigeration chambers maintain foodstuffs at a particular temperature in order to extend the shelf life of foods. This paper deals with an exergy analysis of cold storage intended for freezing fish. The refrigeration chamber cooling system maintains a constant temperature by supplying cold through evaporators, thus compensating for heat losses through the refrigeration chamber walls or due to the impacts of lighting fittings, occasional opening of the door, etc. The refrigeration system is wasteful in terms of energy consumption. From an energy perspective, the upgrading the refrigeration system, involving the capturing of waste heat from the condenser to use the hot side of the cooling system, results in a greater effect, lower energy consumption and, ultimately, financial savings.

Modern refrigeration rooms and cold stores are designed to freeze the largest possible quantity of food in the shortest time possible. This case study involves the storage of fish; freshly caught fish, a highly perishable food, should be stored in a flake ice bath, while frozen fish is stored in frozen fish chambers until taken over by a customer. Refrigeration tunnels operate when necessary, but the storage rooms have to maintain a constant temperature throughout the year. In terms of energy consumption, contemporary systems include new compressor designs with a so-called integrated eco-system, reducing isentropic losses by cooling hot gases during compression and installing a sub-cooler on the condenser side to increase the evaporator cooling power, using little energy. The use of condenser heat is necessary in order to increase the efficiency of the refrigeration system.

This article deals with the calculation of savings, whereby the amount of heat recovered from the condenser unit is based on the equations found in articles by Die Klima und Kaeltetchnik, published in 1987, [1]. The exergy analysis of the upgraded system proves the improvement of refrigeration systems to be reasonable.

2 REFRIGERATION SYSTEM DESIGN

The refrigeration system observed consists of five refrigeration units, the first of which is designed to maintain the temperature of the chambers with the packaging, and a corridor designed for handling. The second unit maintains the temperature of the chambers containing frozen fish. The third cooling unit operates occasionally, as it ensures the functioning of the refrigeration tunnels, freezing approximately 10 tons of fresh fish to -28°C in nearly nine hours of operation. The fourth unit also operates occasionally, producing flake ice. The fifth refrigeration unit operates separately, when necessary. It allows the freezing of each fish separately, [2].

For waste heat recovery from condensers, only those systems that operate constantly throughout the year may be used. These maintain a constant temperature in the refrigeration chambers.

The first system maintains a constant temperature in the fresh fish chambers and operates at an evaporation temperature of +3°C or -8°. A suction pressure regulator needs to be fitted to the suction pipes of the chambers with the evaporation temperature of +3°C. This system is referred to below as the 'plus system'.

The second system, maintaining a constant temperature in the frozen fish chambers, operates at evaporation temperatures of -32°C or -13°C. In this case, a suction pressure regulator is also needed to maintain the evaporating temperature of -32°C in the suction pipe. This system is referred to as the 'minus system'.

The plus system comprises six chambers connected to a compressor set with three compressors. These are four-piston compressors with a two-stage regulation of the operation. The regulation may be performed at six stages. The plus system's cooling capacity is 57 kW, and the condensation heat to be recovered from the system is 77 kW, [2].

The minus system comprises five chambers connected to a generator unit with 2 six-piston compressors, each capable of performing a three-stage regulation. The minus system's cooling capacity is 47 kW and the condensation heat 78 kW, [2].

2.1 Waste heat recovery system

While the condensation temperature of the designed system is 45°C, the hot gases exiting the compressor have a temperature of 76°C. It is established that tap water can be heated from 10°C to 50°C for sanitary use with an additional plate heat exchanger installed before the hot gasses enter the air-cooled condenser.

In accordance with Die Kaelte und Klima Technik, [1], an analysis of possible waste heat recovery systems was made to select an appropriate plate heat exchanger. The decision was made to connect the pressure pipes from the plus system's multi-compressor unit and the minus system's multi-compressor unit with regard to the position of the engine and boiler rooms.

A 40 kW plate heat exchanger is installed in the engine room, using part of the condensation heat of the refrigeration system in question for heating the sanitary water, presented in Fig. 1, before entering the condenser, placed on the roof. Water travels through the plate heat exchanger and transfers heat to the heating system in the boiler room as shown in Fig. 2. The selected condenser is of sufficient size to be able to evacuate condensation heat from the refrigeration system even when the waste heat recovery system is inactive.

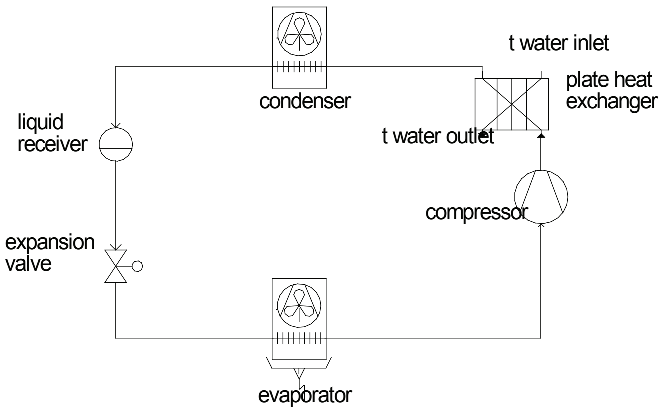

Figure 1: *Refrigeration system with waste heat recovery [2]*

2.2 Boiler room design

The boiler room is located away from the engine room, which is a weakness of the system, as some heat is lost during distribution. The boiler room houses a 500-litre tank, receiving heat by the bottom coil from the waste condensation heat recovery system shown in Fig. 2. The tank is used only for sanitary water in toilets of the office part of the building, in the staff kitchen and bathroom. Tap water is used for the purposes of building cleaning.

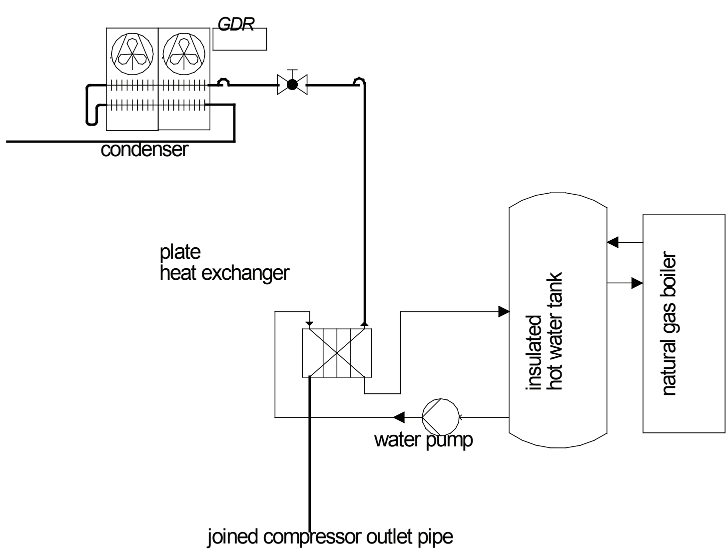

Figure 2: *Waste heat recovery system combined with the heating system [2]*

3 CALCULATION OF WASTE HEAT

The plate heat exchanger, installed as indicated in (Fig. 1), initially recovers the heat occurring in hot gas cooling and then recovers a portion of the heat dissipated in the refrigerant condensation.

To analyse the system, the equations for the calculation of the quantity of condensation waste heat that can be recovered were needed. The equations according to [1] were used, showing that the recovered condensation waste heat is calculated according to Equation 3.1, in which Δh_2 and Δh_1 are the values from the diagram log p – h (Fig. 3).

$$\dot{Q}_w = \dot{Q}_{cond} \cdot \frac{\Delta h_2}{\Delta h_1} \tag{3.1}$$

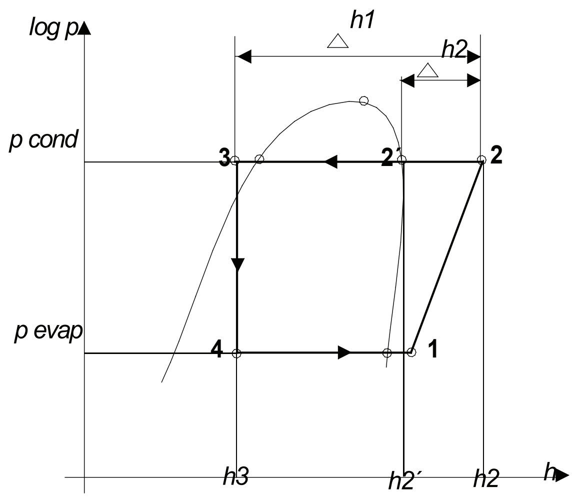

Figure 3: *Values used for the calculation of waste heat [2]*

Given that the waste heat recovery system comprises both the plus and the minus system, separate calculations are required.

3.1 Calculation of waste heat for the plus system

For the given state of operation, the values of enthalpy in the working points were read from the log p – h diagram for Freon R404A [3] and presented in Table 1.

Table 1: *Values of enthalpy used in the calculation for the plus system*

	h (kJ/kg)
h_2	405
$h_{2'}$	380
h_3	265
Δh_1	140
Δh_2	25

Using (3.1), it was calculated that 13.7 kW of waste heat flow may be recovered from the plus system.

3.2 Calculation of waste heat for the minus system

For the given state of operation, the values of enthalpy in the working points were read from the log p – h diagram, for Freon R404A, [3], and are presented in Table 2.

Table 2: *Values of enthalpy used in the calculation for the minus system*

	h (kJ/kg)
h_2	418
$h_{2'}$	380
h_3	266
Δh_1	152
Δh_2	38

Using (3.1), it can be calculated that 19.5 kW of waste heat flow may be recovered from the minus system.

The total waste heat flow that can be recovered for sanitary water heating purposes is 33.2 kW.

As (3.1) was only found in older references and the use of condenser waste heat had become common knowledge over years of practice, the calculation of its amount with (3.1) became a useful instrument.

4 CALCULATION OF COST SAVINGS

Waste heat recovered from a refrigeration system operating 3,900 hours per year amounts to 129,480 kWh, [2]. According to (4.1), the amount of heated water can be calculated.

$$\dot{V} = \frac{\dot{Q}_w}{c_p \cdot \Delta t \cdot \rho} \tag{4.1}$$

Over a period of one year, the refrigeration system can heat approximately 2,774 m^3 of tap water from 10°C to 50°C using the condensation heat. In order to heat the same amount of water, the quantity of 11,262 m^3 natural gas would be required. In three years, the cost saving would account for €16,724 when calculated with the average natural gas price over the last six years, i.e. €0.495 for 1 m^3.

In view of the fact that the consumers in the building need a lower quantity of waste heat, it is established that they do not need a gas boiler for sanitary water heating. The given refrigeration system contains a sufficiently high quantity of waste heat for heating the sanitary water.

The price for one extra plate heat exchanger, extra valves, and tubes is approximately €7,500. The diagram presented in Fig. 4 shows the number of months in which the investment repays its costs over savings, taking in account the price variable for 1 m^3 of natural gas over the previous six years.

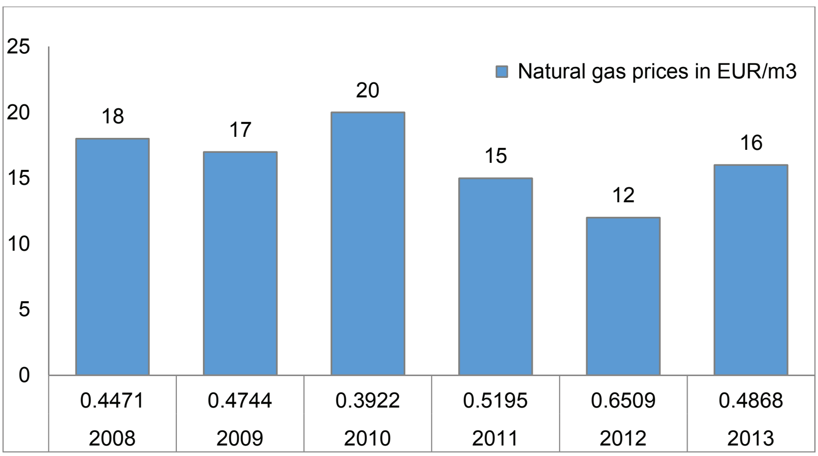

Figure 4: *The number of months to repay investment over savings*

5 EXERGY ANALYSIS OF THE REFRIGERATION SYSTEM

The cost-benefit analysis has revealed that upgrading the refrigeration system is financially viable. Given that energy may be used for refrigeration and heating, it may be argued that the upgrading results in an increase in the exergy of the system.

The exergy method is a functional means of promoting the effectiveness of energy-resource use, [4]. To begin the calculation, the specific exergy was calculated using (5.1).

$$e = (h - h_0) - T_0(s - s_0) \tag{5.1}$$

where h_0 and s_0 are specific enthalpy and enthropy at surroundings temperature, respectively, [4].

For each state, the values in Table 3 were used.

Table 3: *Values of specific enthalpy, specific entropy [3] and calculated specific exergy calculation (5.1) for the plus system*

	State	h (kJ/kg)	s (kJ/kgK)	e (kJ/kg)
0	Surroundings	395	1.854	0
1	Compression start	368	1.636	37.17
2	Condensation start	405	1.659	67.13
3	Expansion start	260	1.198	57.03
4	Evaporation start	259	1.225	48.57

To calculate the exergy efficiency of the system, the equations according to [5] were used.

5.1 Exergy losses in a compressor

Exergy losses in a compressor occur due to electromechanical conversion and isentropic efficiency compression and can be calculated using (5.2).

$$e_{comp} = (1 - \eta_{em}) \cdot e_{in} + \eta_i \cdot e_{in} + e_1 - e_2 \tag{5.2}$$

For 90% electromechanical conversion efficiency and 80% isentropic compression efficiency in a compressor, a 21.7% loss was calculated regarding the exergy when entering the system.

5.2 Exergy losses in an evaporator

Evaporators are units through which the supplied exergy is lost due to the mass flow and is calculated using (5.3).

$$e_{evap} = e_4 - e_1 - e_{cold} \tag{5.3}$$

The exergy loss due to the mass flow rate accounts for 29.8% of the supplied exergy. An evaporator is a working unit that evacuates the heat from a room. Therefore, the percentage of the exergy loss is reduced by thermal exergy of the heat which is transferred from the chamber.

Thermal exergy load of heat is calculated using (5.4), [6].

$$e_{cold} = q_{evap} \cdot \left(1 - \frac{T_0}{T_{INsr}}\right) \tag{5.4}$$

Where the surroundings temperature T_0 of 293 K and T_{INsr} mean temperature of the air into which the evaporator dissipates the heat out of the chamber, the value of 270.5 K, were used. The total exergy loss through the evaporator is 5.5% of the inlet exergy. The exergy of heat inlet in the evaporator is 24.3%.

5.3 Exergy losses in an expansion valve

The exergy loss is calculated using (5.5) in an expansion valve, where an adiabatic system conversion takes place, solely in terms of the exergy supplied and recovered.

$$e_{exp} = e_3 - e_4 \tag{5.5}$$

The calculated loss of the exergy supplied to the expansion valve is 22.1%.

5.4 Exergy losses in a condenser

The loss of exergy through an air cooled condenser comprises the supplied and recovered exergy flow through the condenser (5.6).

$$e_{cond} = e_2 - e_3 \tag{5.6}$$

It was calculated that 26.4% of the supplied exergy is lost in the condenser.

Exergy losses and gain are presented in Table 4 and in (Fig. 5) according to Rant, [7].

Table 4: *Values of exergy inlet losses and gains*

	Exergy loss (%)
Compressor	21.7
Expansion valve	22.1
Evaporator	5.5
Condenser	26.4
	Exergy gain (%)
Heat outlet of the chamber	24.3

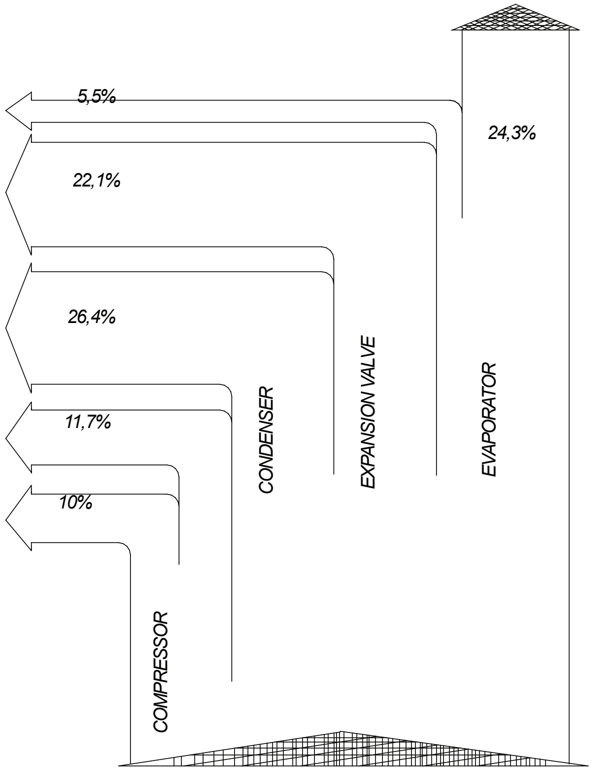

Figure 5*: Exergy Rant diagram for refrigeration system*

6 EXERGY ANALYSIS OF THE REFRIGERATION SYSTEM UPGRADED WITH HEAT RECOVERY

In the refrigeration system upgraded with a waste heat recovery, the percentage of the lost exergy through the condenser is changed, as a portion of exergy is recovered in the form of heat for heating purposes.

The calculation of the exergy loss in the condenser was repeated, due to added state of calculation values to Table 3, and are presented in Table 5.

Table 5: *Values of specific enthalpy, specific entropy [3] and calculated specific exergy calculation (5.1) for the plus system upgraded with heat recovery*

	State	h (kJ/kg)	s (kJ/kgK)	e (kJ/kg)
0	Surroundings	395	1.854	0
1	Compression start	368	1.636	37.17
2	Heat recovery start	405	1.659	67.13
2’	Condensation start	383	1.588	65.94
3	Expansion start	260	1.198	57.03
4	Evaporation start	259	1.225	48.57

6.1 Exergy losses in a condenser of the system using waste heat

The exergy losses in an air cooled condenser are calculated using (6.1). As before, exergy is lost due to the mass flow, but the losses are considered at the flow through state 2.

$$e_{cond} = e_{2'} - e_3 \qquad (6.1)$$

The exergy loss due to the mass flow amounts to 23.3% of the supplied exergy in the system.

In a plate condenser, in which heat is recovered to the sanitary water heating system, a portion of exergy is used for heating. Given that a plate heat exchanger is also a unit causing specific exergy losses due to the mass flow, this portion of the lost exergy should also be taken into consideration.

Thermal exergy load of heat calculated with (6.2) according to [6].

$$e_{heat} = q_w \cdot \left(1 - \frac{T_0}{T_{OUTsr}}\right) \qquad (6.2)$$

Where T_0 is the surroundings temperature of 293 K and T_{OUTsr} value of 303 K is median temperature of water into which the condenser dissipates the heat. Thermal exergy through the plate heat exchanger is 2% of the inlet exergy, whereas the exergy loss due to the mass flow through the plate heat exchanger, calculated with (6.3), is 3.1% of the exergy inlet.

$$e_w = e_2 - e_{2'} \qquad (6.3)$$

Altogether, the exergy loss through the plate heat exchanger is 1.1% due to exergy loss reduction by 2%. The waste heat recovery system represents the possibility of increasing the exergy of the refrigeration system. Exergy losses and gains are presented in Table 6 and in (Fig. 6) according to [7].

Table 6: *Values of exergy inlet losses and gains for heat recovery*

	Exergy loss (%)
Compressor	21.7
Expansion valve	22.1
Evaporator	5.5
Condenser	26.4
Plate heat exchanger	1.1
	Exergy gain (%)
Heat recovery	2
Heat outlet of the chamber	24.3

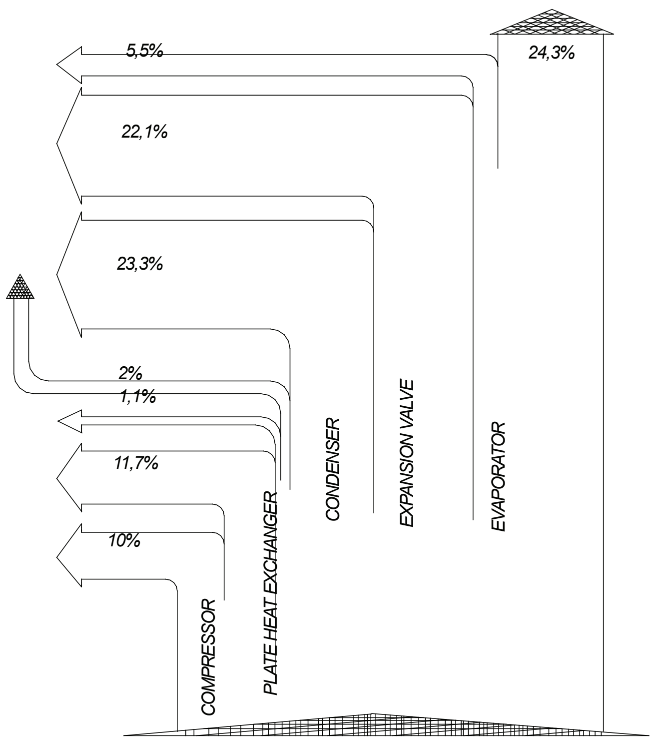

Figure 6: *Exergy Rant diagram for refrigeration system with heat recovery*

7 CONCLUSION

This case study shows the quality of refrigeration project applicable in all constant operating refrigeration systems with higher condensation temperatures. To avoid problems with Legionella infections, additional heaters need to be installed.

The exergy calculations of both systems show that the exergy efficiency is increased in the waste heat recovery system. It is also more efficient from an energy perspective. The cost-benefit analysis shows that via a small additional contribution and a proper selection of components it is possible to influence the long-term efficiency of the system. The waste condensation heat recovery systems are simple, and it is reasonable to use them in a refrigeration system operating throughout the year. The investment pays off approximately in one year.

References

[1] *Enthizungleistung, Die Kaelte und Klima Technik*, 1987, Vol. 10

[2] **I. Tršelič**: *Exploitation of waste heat in refrigeration*, Master's thesis, 2nd level, Faculty of Energy Technology, University of Maribor, 2012

[3] Solvay, *Chemicals Diagrams*, 2011

[4] **M. Farmahini-Farahani, S. Delfani, J. Esmaeelian**: *Exergy analysis of evaporative cooling to select the optimum system in diverse climates*, Energy, 2012, Vol. 40 Issue 1, p.250–257

[5] **T. Obersnu**: *Strojno hlajenje in gretje*, Tehniška založba Slovenije, 1991

[6] **R. Chengqin, L. Nianping, T. Guangfa**: *Principle of exergy analysis in HVAC and evaluation of evaporative cooling schemes*, Building and Environment, 2002, Vol. 37 Issue 11, p. 1045–1055

[7] **Z. Rant**: *Termodinamika knjiga za uk in prakso*, Ljubljana, 2007

Nomenclature

e	specific exergy
h	specific enthalpy
Q_w	waste heat
Q_{cond}	condensation heat
s	specific entropy
Δt	temperature difference
T_0	environment temperature
T_{INsr}	median temperature in the evaporator
T_{OUTsr}	median temperature in the condenser
V	volume flow
η_{em}	electromechanical efficiency
η_i	isentropic efficiency