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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

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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.

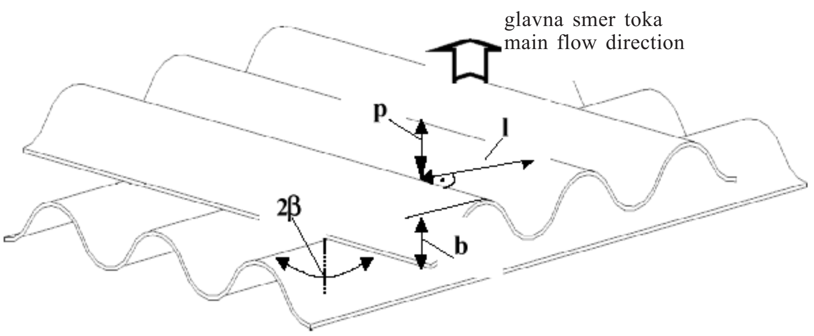
(Keywords: heat exchangers, plate heat exchangers, flow visualizations, measurement characteristics)

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^o).



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:

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

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

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

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

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

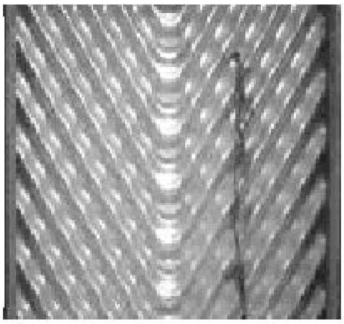
Lamela 28°

Plate 28°

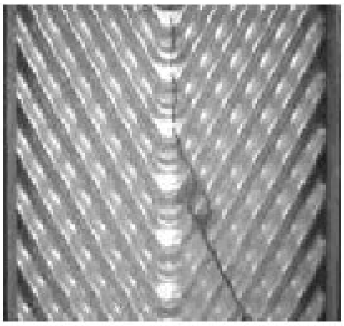
a) barvilo, vbrizgano blizu prosojnega zidu, navzkrižni tok, povečanje utorne komponente z Re

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

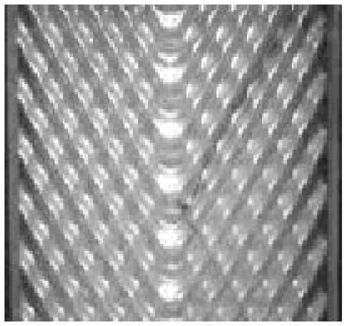
Re = 0,1



Re = 10



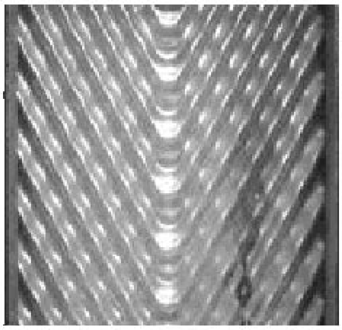
Re = 250



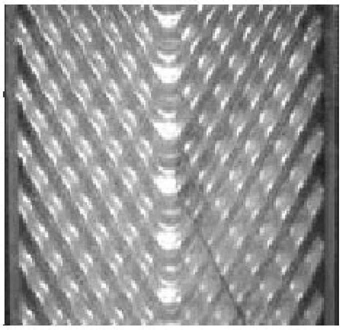
b) barvilo, vbrizgano v srednji del križnega toka prečne površine (osnovna celica), prebrana vzdolžna komponenta in prevlada utorov pri večjem Re

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



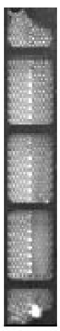
Re = 250



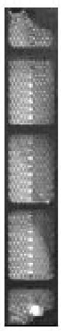
c) barvilo, vbrizganov spodnji del desne strani kanala, popolno pomanjkanje mešanja med dvema lamelnima polovicama pri manjšem Re

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



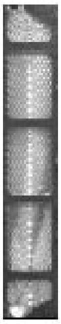
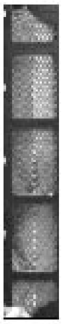
Re = 85



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

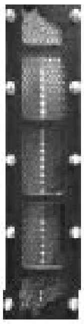
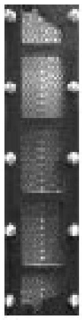
Re= 13 Re = 140

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

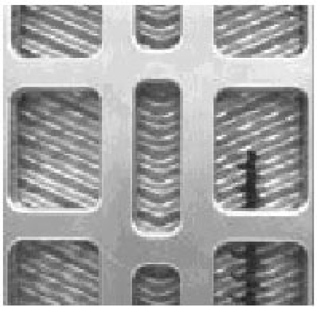
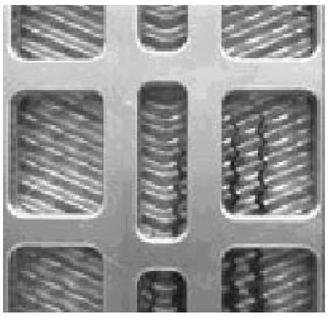
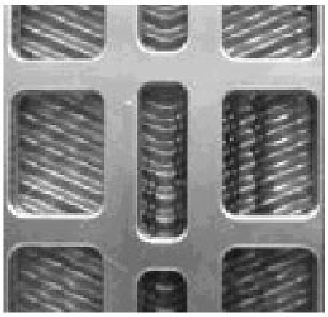
Lamela 61°

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

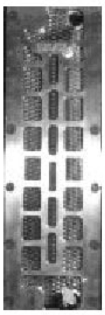
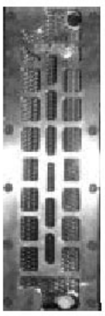
Re = 0,5 Re = 10 Re = 60

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	$D_h = \frac{4\ x\ \text{prostornina/volume}}{\text{mokro območje/wetted area}} = \frac{2b}{\phi}$	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 β=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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