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INFLUENCE OF CHEVRON PLATES GEOMETRY ON PERFORMANCES OF PLATE HEAT EXCHANGERS

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Prethodno priopćenje

The paper presents the investigation on the influence of different geometric parameters such as the chevron angle β, pressing depth b and corrugation wave length l on thermal-hydraulic performances of corrugated channels, commonly employed in plate heat exchangers. In order to fully understand a rather complex flow phenomenon occurring in corrugated channels, a number of dye based visualization tests have been conducted on two channels with chevron angles β=28° and β=61° at low Re-number flow conditions. The existence of two flow components has been recorded. The influence of flow components on the heat transfer depends mainly upon the angle β and Re-number as well as on the aspect ratio b/l. The exception are plates with the angle β<45° where the aspect ratio b/l does not significantly influence neither thermal nor hydraulic performances. Also, the influence of b/l on heat transfer declines as Re- numbers decrease. Thermal-hydraulic performances are evaluated in terms of the heat transfer coefficient, pressure drop and area goodness factor calculated from experimental data reported in the literature. Results indicate higher increase of the pressure drop relative to increase in the heat transfer for plates with deeper grooves (higher b/l) at fixed Re-number and angle β.

Keywords: *corrugated channels, flow, plate heat exchangers, thermal-hydraulic performances, visualization*

Utjecaj geometrije V-ploča na karakteristike pločastih izmjenjivača topline

Preliminary notes

U članku su predstavljeni rezultati istraživanja utjecaja različitih geometrijskih parametara, poput kuta V-žljebova β, dubine žlijeba b i širine žlijeba l, na toplinsko-hidrauličke karakteristike valovitih kanala kakvi se uobičajeno koriste u pločastim izmjenjivačima topline. Kako bi se u potpunosti objasnio složeni mehanizam strujanja u valovitim kanalima, proveden je određen broj vizualizacija strujanja u dva kanala s kutovima V-žljebova od β =28° i β =61° pri malim vrijednostima Re-brojeva. Zabilježeno je postojanje dviju komponenti strujanja. Njihov utjecaj na izmjenu topline najviše ovisi o kutu β i Re-broju, kao i o omjeru b/l. Iznimka su ploče s kutom β <45° kod kojih omjer b/l nema značajniji utjecaj niti na toplinske niti na hidrauličke karakteristike. Također, utjecaj b/l na prijelaz topline se smanjuje kako se smanjuju Re-brojevi. Toplinsko-hidrauličke karakteristike su vrednovane preko koeficijenta prijelaza topline, pada tlaka i faktora dobrote koji su izračunati iz eksperimentalnih rezultata dostupnih u literaturi. Rezultati upućuju na znatnije povećanje pada tlaka u odnosu na povećanje intenziteta prijelaza topline kod ploča s dubljim žljebovima (tj. većim b/l) pri zadanim vrijednostima Re-broja i kuta β.

Ključne riječi: *valoviti kanali, strujanje, pločasti izmjenjivači topline, toplinsko-hidrauličke karakteristike, vizualizacija*

1 Introduction
Uvod

In spite of a recent remarkable increase of plate heat exchangers on the heat transfer equipment market, a relatively sparse amount of information on basic flow mechanism and influence of plate geometry on exchanger thermal-hydraulic performances are available in the open literature. The reported results from visualization tests ([1, 2]) and mass transfer technique ([3, 4, 5, 6]) to record either flow patterns or local values of mass (heat) transfer coefficient are, however, not sufficient to completely recognize the basic flow mechanism involved in heat and momentum transfer as well as to evaluate the influence of geometric parameters on the exchanger performance. This work addresses these topics that are crucial for further improvement of exchanger performances. The basic geometry used in all types of PHEs consists of a number of narrow channels each composed by two corrugated plates with chevrons inclined by the angle β to the main flow direction and running in opposite directions on adjacent plates (Fig. 1). Such arrangement produces a complex 3D flow pattern, whereby the transition from laminar to turbulent flow starts already at Re=10. Fully turbulent flow is achieved at $Re \cong (300 \div 700)$ depending upon the angle β, as the most influencing parameter (e.g. [2, 4, 7]). Interactions between substreams flowing along chevron furrows accompanied by generation of secondary swirl flows are responsible for high mass and heat transfer coefficients. In order to explore the behavior of a fluid passing through corrugated channels and to record the flow path, it was decided to run visualization tests primarily in the laminar flow regime, by injecting a dye at certain points within the flow cross section. This simple technique, applied at low velocities when swirling diminishes, offered an opportunity to observe the complex movement of fluid streams by bare eye. Channels with different chevron angles β=28° and β=65°, but with the same pressing depth to wave length ratio b/l were tested in order to evaluate the influence of the angle and Re-number on the flow pattern in these geometries which correspond to the lower and upper limits in commercial applications, respectively. From the previously reported visualization results ([2, 8, 9]) it was clear that the wavy longitudinal flow pattern occurs in the channels with angles higher than $\beta=(45 \div 50)°$ while criss-crossing flow occurs at lower angles in the transient and turbulent flow regime. Since no data was previously reported for purely laminar flow this work provides complementary information for this important flow regime encountered in applications with secondary refrigerants, processing of viscous fluids such as polymers, pseudo-plastics, in food industry etc.

The influence of the ratio *b*/*l* on flow pattern and thermal-hydraulic characteristics was investigated by Gaiser and Kottke [4] and Okada et al. [13], but only at fully turbulent flow conditions and these results are discussed here. The results from the present work allow for speculation about the influence of *b*/*l* on the channel performances at lower Re-numbers. A comprehensive literature survey of experimental data for heat transfer and pressure drop in PHEs ([7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18]) proved a remarkable disagreement between data recorded by different authors at the same Re-numbers and angles but different aspect ratios *b*/*l*. This is attributed to the influence of *b*/*l* on performances but also to different definitions of dimensionless groups involved in describing the heat transfer and pressure drop characteristics, as discussed in detail in [19].

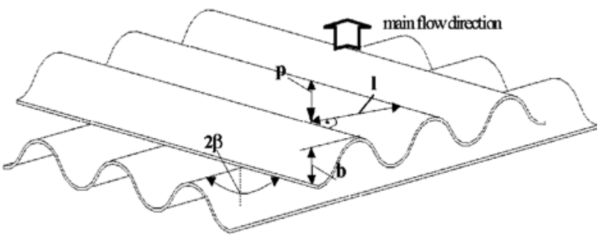

Figure 1. 3D channel composed by two corrugated chevron plates
Slika 1. 3D kanal sastavljen od dvije valovite ploče

2 The experimental apparatus and procedure
Mjerna linija i postupak

The visualization tests of the flow in chevron corrugated channels were performed with two modeling channels consisting of plates with the angles β=28° and β=61° and the aspect ratio b/l=0,28. Dye was injected at certain points into the upward flow of aqueous glycerol and water at the flow conditions corresponding to the ranges Re=(0,1÷20) and Re=(20÷250) respectively. Each model-channel is composed of one metal plate normally used in PHEs and one 8 mm thick transparent plastic plate with identical corrugations on its inner side. The plate with the angle β=28° is the same as those normally used in gasketed PHEs and as such it was assembled together with the plastic one within the metal frame and pressed by bolts. In order to allow for visual observation of the flow pattern, a number of windows were made in the frontal metal frame plate covering the whole length and width of the channel as well as the distribution areas around the inlet and outlet ports. Similarly, the other channel consists of one metal and one transparent plastic plate, both with the angle β=61° having no gaskets as it represents the geometry used in brazed PHEs. Therefore, the plastic plate was glued to the metal one and, in order to avoid fluid leakage, additionally pressed by a metal frame also having a number of windows. A dye (methyl blue) was injected into the channel via a hypodermic tube through the holes drilled into the plastic plate. This enabled changing of the injection position within the channel cross section i.e. within the gap between plates which is max. 4 mm. The schematic of the test rig is shown in Fig. 2.

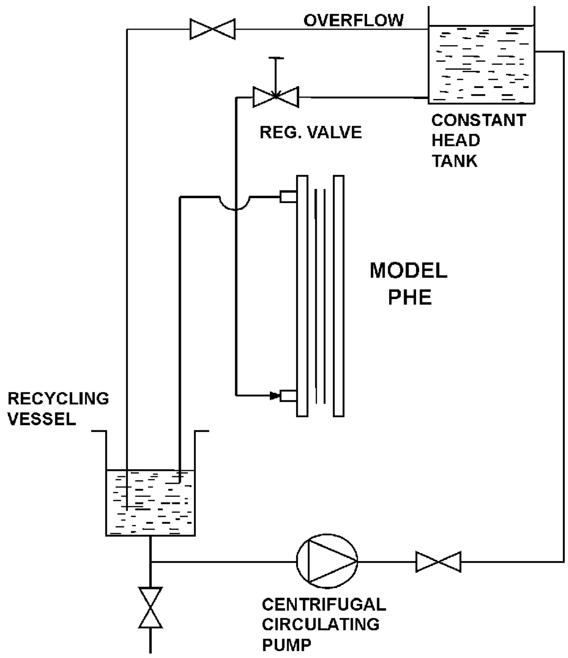

Figure 2. Experimental set-up
Slika 2. Mjerna linija

In order to avoid any possible flow fluctuations present when a pump is used to circulate a fluid, a constant head device was used instead. The working fluid was delivered from the open storage tank placed at the top of the rig to the inlet port of the channel via a transparent plastic tube. The outlet port was connected by a plastic tube to the receiver at the bottom of the system. Constant head in the upper storage tank was maintained by connecting an overflow pipe to the receiver, also open to the atmospheric pressure. A circulating pump was used to supply the upper storage tank with the same amount of fluid that was extracted through the overflow and channel supply pipe. A needle valve was used to regulate the flow rate through the channel. That allowed for a fine adjustment of the volume flow rate to the desired Re-number. The volume flow rate was determined by collecting the drained fluid in a calibrated tube while simultaneously recording the time. That allowed for accurate measurements of volume flow rates as small as 0,01 l/min at Re=10. Methyl blue was used as a dye due to its solubility in both water and glycerol as well as due to the similar density (minimizing gravity effects) at the high concentrations needed to make it highly visible within the other fluids.

The flow pattern was recorded by a digital video camera connected to a personal computer. Pictures were taken at appropriate time intervals after introduction of the dye. The minimum recording time interval between two pictures was 1/10 sec which enabled recording of the dye flow path after first injection, even at high velocities corresponding to Re-numbers as high as *Re*=500. In order to produce clear pictures at all flow conditions and injection points, dye was introduced in one short pulse, in a number of discrete pulses or continuously as indicated at each picture in the subsequent text.

3 Results
Rezultati

Visualization results are presented in Figures 5 to 8. They reveal the presence of basically two substreams flowing along the furrows in the opposite plates (channel walls).

Certain parts of the substreams mix. The flow pattern is characterized by the size of those parts and the magnitude of the interactions is dependent primarily upon the chevron corrugation angle β as well as upon the Re-number and the aspect ratio b/l.

Interactions between two substreams cause the appearance of basically two characteristic flow components (parts of substreams) referred to as the longitudinal and the furrow substream, and it is believed that both are occurring simultaneously in both tested channels. The longitudinal component refers to the part of the fluid flowing alternatively along adjacent plates through respective furrows. The furrow component denotes the part of a fluid flowing through the furrow along one plate without change of direction within each encountered cell. The change in direction occurs at the plate edge and/or center line of the plate where furrows change direction. Positions of two components within the element (basic cell) of the corrugated channel are schematically shown in Fig. 3.

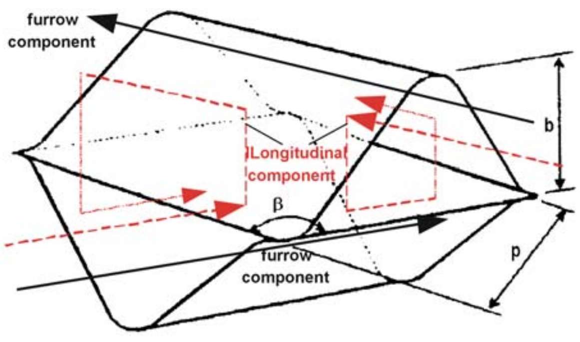

Figure 3. Occurrence of two flow components within the basic cell
Slika 3. Pojava dviju komponenti strujanja u osnovnoj ćeliji

3.1 Channel with β=61°
Kanal s β=61°

The longitudinal component is the dominant one for the flow in the channel with the angle β=61°, producing the 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. This flow phenomenon can be explained as follows: each substream after entering the basic cell (Fig. 3) changes direction because it is retarded by the incoming opposite substream and pushed first to the cell wall and then following the wall shape proceeds to the opposite adjacent plate (Fig. 4). One minor part of the substream, which is not colored by dye, proceeds in the first direction along the furrow wall without change of direction. It is mixed to some extent with the main part of the opposite substream, which had changed direction before (i.e. the opposite longitudinal component). This change of direction is believed to be accompanied by strong mixing within the cell, resulting in higher heat transfer coefficient and higher pressure drop. This process is being repeated in each cell. The colored fluid in the central part of the longitudinal component remains very clearly visible during its path through a number of cells indicating no mixing with the minor furrow component. Therefore, mixing occurs primarily between outer parts of these two components. At very low Re-numbers (*Re*=5) the longitudinal flow is very pronounced (Fig. 5). The main parts of the substreams flow almost straight upward without even partially following the furrows as occurs at *Re*=10 due to higher influence of the furrow component on the flow at increased velocities. At higher Re-numbers two longitudinal components occupy large area of the cell being completely coupled (mixed) at *Re*>60 indicating an intensification of interactions between the flow components. At higher Re-numbers, there is an existence of two areas of maximum velocities within the longitudinal component, one of which is closer to the contact points. Elevated rates of mass transfer at these positions within the basic cell were also recorded by Heggs et al. [5].

3.2 Channel with β=28°
Kanal s β=28°

When the angle β is lowered, the retardation effect is less pronounced due to the lower velocity vector component in the direction of the opposite substream $u\cdot\cos(2\beta)$ (Fig. 4).

Here, the main part of each substream after entering the cell proceeds in the first direction following the furrows on adjacent plates (Fig. 6 and 7). The only exception is the flow at extremely low Re-number (*Re*=0,1) when the longitudinal component is dominant. Also, introduction of dye into the central part of the channel (cell) proved there is some minor part of the fluid that changes direction in each cell (Fig. 8). This longitudinal component flows alternatively at the edges of both substreams following to some extent the shape of encountered cell walls (but always within the central part of the channel cross section). Mixing between two substreams is, therefore, less thorough and the effective flow length shorter, which explains the lower heat transfer coefficients and friction factors for plates with lower angle β. As it is case for the 61° plate, an increase of the flow velocity, i.e. Re-number, promotes the furrow component, and the longitudinal component completely disappeared as the Re-number was increased up to Re=250, even when dye was introduced in the middle part of flow cross sectional area (Fig. 8). When the Re-number (velocity) is higher, the change in momentum due to the change of the substream's direction is also higher. This explains lower tendency to the wavy longitudinal flow pattern at higher Re-numbers.

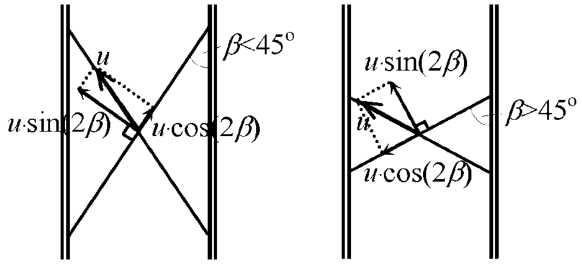

Figure 4. The velocity components of one substream flowing along a furrow of one plate at angles β<45° and β>45°
Slika 4. Komponente brzine podstruje koja prati žlijeb jedne od ploča pri kutevima β<45° i β>45°

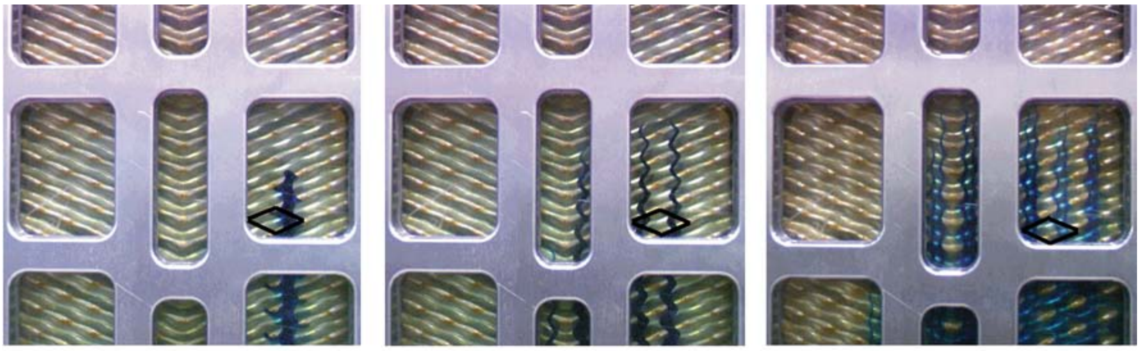

Figure 5. Flow pattern in the channel with β=61° at different Re-numbers, (basic cell is indicated in the full line)
Dye injected at central part of the cross section area in one short pulse, wavy longitudinal flow, increase of the furrow component with Re and more thorough mixing of the two substreams within the cell at higher Re-numbers
Slika 5. Profil strujanja u kanalu s β=61° pri različitim Re-brojevima, (osnovna ćelija je naznačena punom linijom)
Tinta ubačena u sredini poprečnog presjeka strujanja, longitudinalano strujanje, povećanje komponente u smjeru žlijeba s Re-brojem i intenzivnije miješanje dviju podstruja u ćeliji pri većim Re- brojevima.

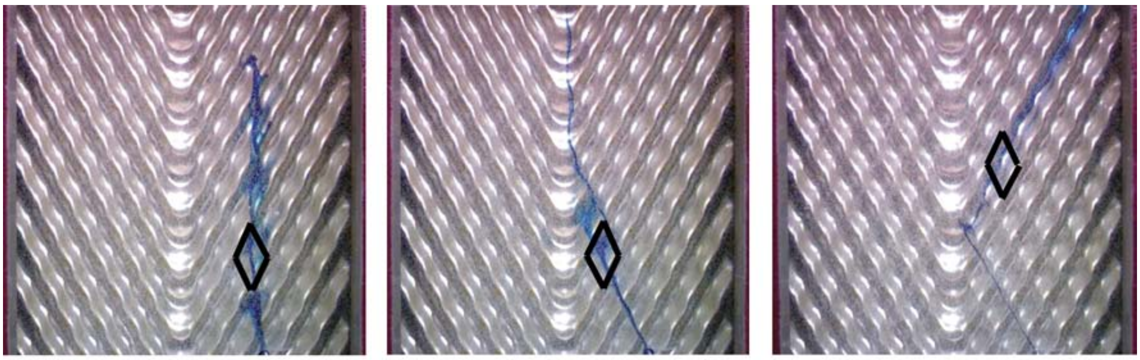

Figure 6. Flow pattern in the channel with β=28° at different Re-numbers, (basic cell is indicated in the full line)
Dye injected close to the transparent wall in a number of discrete pulses, criss-cross flow, dominance of the longitudinal component at very low Re, increase of the furrow component with Re-number
Slika 6. Profil strujanja u kanalu s β=28° pri različitim Re-brojevima (osnovna ćelija je naznačena punom linijom)
Tinta ubačena impulsno u neposrednoj blizini prozirne stijenke, criss-cross strujanje, dominacija longitudinalne komponente pri vrlo malim Re-brojevima, povećanje komponente u smjeru žlijeba s Re-brojem

In Fig. 4 u is the main substream velocity, $u\cdot\sin(2\beta)$ is the velocity component perpendicular to the other substream main flow direction-induces swirl flow, $u\cdot\cos(2\beta)$ is the velocity component parallel to the other substream main flow direction-responsible for the change in direction at $\beta<45^{\circ}$.

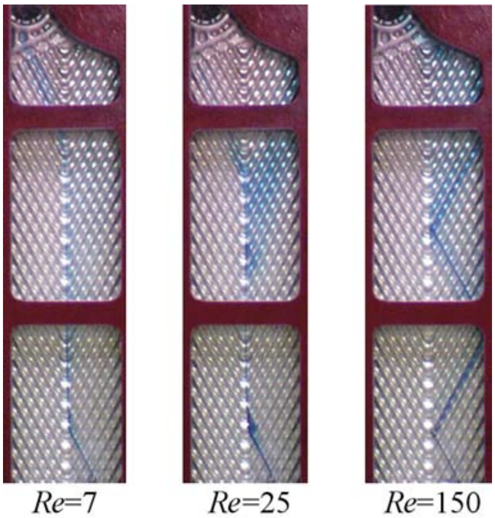

Figure 7. Flow pattern in the channel with β=28° at different Re-numbers
Dye injected close to the transparent wall in a number of discrete pulses, criss-cross flow, increase of the furrow component with Re, "channeling" along the middle line at lower Re, reflectance at the middle line at higher Re-number
Slika 7. Profil strujanja u kanalu s β=28° pri različitim Re-brojevima
Tinta ubačena impulsno u neposrednoj blizini prozirne stijenke, criss-cross strujanje, povećanje komponente u smjeru žlijeba s Re-brojem , "kanaliziranje" uz centralnu liniju ploče pri manjim Re, promjena smjera strujanja kod centralne linije pri većim Re-brojevima

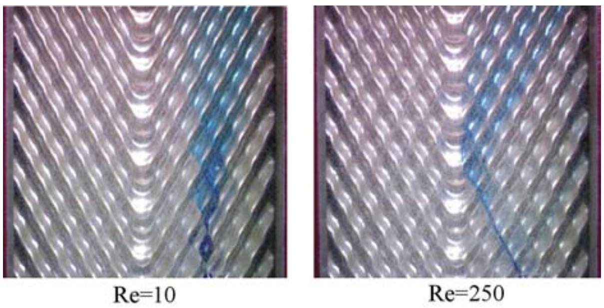

Figure 8. Flow pattern in the channel β=28° at different Re-numbers
Continuously injected dye in the middle part of flow cross sectional area (basic cell), evidence of the presence of the longitudinal component in the central part of the cell, complete dominance of the furrow component at higher Re-numbers
Slika 8. Profil strujanja u kanalu s β=28° pri različitim Re-brojevima
Kontinuirano ubacivana tinta u centralni dio poprečnog presjeka strujanja (osnovne ćelije), potvrda prisutnosti longitudinalne komponente u središnjem dijelu ćelije, potpuna dominacija komponente u smjeru žlijeba pri većim Re-brojevima

4 Discussion

Rasprava

4.1 Influence of *b*/*l* and *β* on performances at different Re-numbers

Utjecaj *b*/*l* i *β* na karakteristike pri različitim Re-brojevima

The tests carried out by Gaiser and Kottke [4] confirm the intuitive assumption that narrower corrugations (plates with higher aspect ratios *b/l*) promote pipe flow of the substreams i.e. the furrow component. That in turn affects the thermo-hydraulic performance of the channel. In the channels with higher angles, i.e. predominant influence of the longitudinal component, it is believed that this promotion of the furrow component is beneficial for the heat transfer since the two main substreams are mixed more thoroughly within the cell. In [4] it was shown that increase of the furrow component when *b/l* is raised, results at higher angles (β>45°) in more homogeneous distribution in local heat transfer and higher heat transfer rate (Fig. 9). Lower *b/l* will increase the influence of the longitudinal component, which is desirable for the channels with lower angles (β<45°) as it means better mixing between the two dominant furrow components. On the other hand, as is shown in [20] decrease of *b/l* will lead to lower heat transfer coefficients in ducts of sinusoidal cross section. This counteracts the effect of increased mixing. Results by Gaiser and Kottke [4] show increase of Nu-number and friction factor with b/l as a parameter for different angles at *Re*=2000 (Fig. 9). Their results are modified to fit the definitions of the angle β and the wave length shown in Fig. 1.

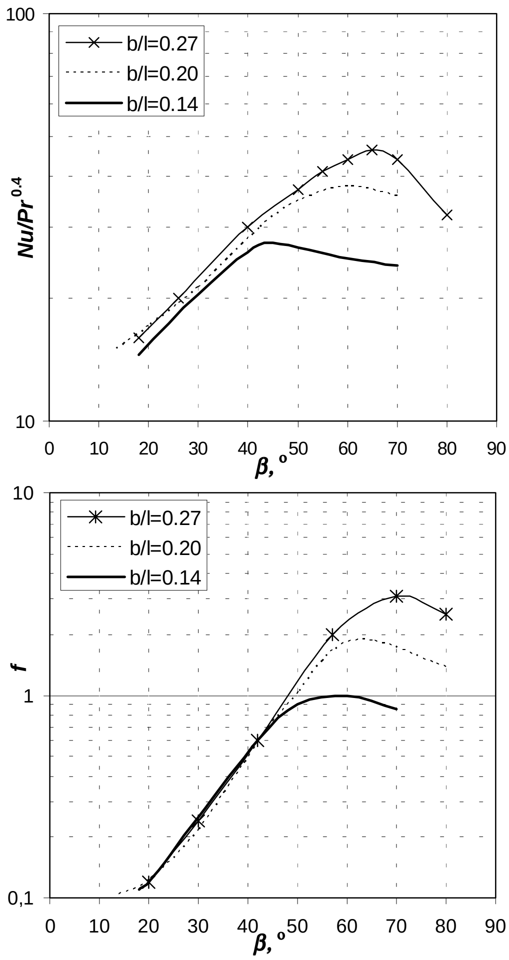

Figure 9. The influence of the aspect ratio b/l and the angle β on heat transfer and pressure drop characteristics of chevron channels at Re=2000, calculated using the experimental results from [4]
Slika 9. Utjecaj omjera b/l i kuta β na prijelaz topline i pad tlaka u V-kanalima pri Re=2000, izračunato iz eksperimentalnih podataka iz [4]

At lower angles the influence of *b/l* on heat transfer is considerably lower than at higher angles. This could be the result of the described mutual counteracting effects between increased mixing and less favorable channel shape. At higher angles an increase of the aspect ratio *b/l* always gives higher Nu-numbers and friction factors.

It is also interesting to notice the decrease of the Nu-number and friction factor after reaching the maximum at the certain angle. It is believed that further increase of the angle leads to flow separation of the dominant longitudinal component at the lee crests. At this angle the flow starts to possess the characteristics of the flow in corrugated ducts with β=90°. The decrease of the friction factor appears to be less pronounced, which means more rapid decrease of the channel goodness factor (especially for the plate with *b/l*=0,14). Furthermore, a decrease of *b/l* should promote the influence of the longitudinal component and separation will start to influence performance at lower angles. Since at lower Re-numbers the longitudinal component is more dominant, it is expected that the maximum heat transfer and pressure drop will occur at lower angles than it is the case at *Re*=2000 (Fig. 9).

At low Re-numbers the longitudinal component will dominate the flow pattern to such an extent that plates with different angles might have similar heat transfer coefficients. Tests carried out by present authors ([19]) on the channels with the same *b/l* indicate no significant increase in the heat transfer coefficient at *Re*<10 when the plate with the angle β=61° is compared to the plate with β=28°. The pressure drop, however, remains noticeably higher with the higher angle. Considering the influence of *b/l* on thermal performances, the same trend can be observed from Fig. 10, showing decreasing influence of *b/l* on the heat transfer coefficient as Re-number drops.

This is probably due to the higher change in momentum of the longitudinal component caused by the changing direction in successive cells. More experiments are needed to explain the influence on the channel performance of a variation of the aspect ratio *b/l* at low Re-numbers.

4.2 Thermal-hydraulic characteristics

Toplinsko-hidrauličke karakteristike

Based on the experimental results reported by Okada et al. [13] in terms of $Nu/Pr^{1/3}$ in dependence on the Re-number, calculations were made to asses the heat transfer capacity of the exchanger when *b/l* is raised. Values of heat transfer coefficients for three tested plates of equal projected area, equal mean distance (flow cross-sectional area) and equal chevron angle (β=60°) are plotted as a function of Re-number defined for one reference plate - $Re_{(b/l=0,27)}$ which allowed for comparison of thermal performances at

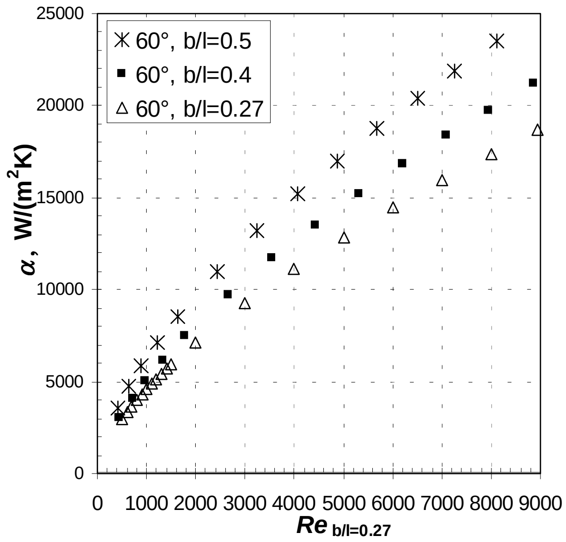

Figure 10. The effect of the aspect ratio b/l on heat transfer coefficient referred to the projected plate heat transfer area at identical mass flow rate, calculated from the experimental data from [13]
Slika 10. Utjecaj omjera b/l na koeficijent prijelaza topline svedenog na projiciranu površinu pri identičnim masenim protocima, izračunato iz eksperimentalnih podataka iz [13]

equal mass flow rates. Hence, the following correlation was used in expressing given initial values for $Nu/Pr^{1/3}$ as a function of $Re_{(b/l=0,27)}$

$$\frac{\mathrm{Re}}{\mathrm{Re}_{b/l=0,27}}=\frac{d_h}{d_{b/l=0,27}}\,. \qquad (1)$$

In addition, values for α are referred to the projected area, which together with provided an equal distance between plates (flow area) enables comparison in terms of heat transferred per unit volume, i.e. channel volume needed to meet a specified heat load. Under the constraint of fixed temperature difference between the wall and bulk fluid the heat transfer coefficient α is directly proportional to the heat exchanged in the heat exchanger and it may be written

$$\frac{\alpha}{\alpha_{b/l=0,27}}=\frac{\dot{Q}}{\dot{Q}_{b/l=0,27}}\,. \qquad (2)$$

From the diagrams below it can be seen that the channels with *b/l*=0,5 are capable of exchanging up to 30 % more heat at fixed channel volume and equal mass flow than the channel with *b/l*=0,27. It was shown in [19] that the heat transfer coefficient referred to the actual heat transfer area instead of the projected one is no more than 10 % higher for the plate with *b/l*=0,5 when compared to the other two plates at fixed Re-number.

To account also for the pressure drop (Fig. 11) the area goodness factor *j/f* is a suitable figure of merit (Fig. 12) since it is independent of the hydraulic diameter (Eq. 3):

$$\frac{j}{f}=\frac{Nu\,\mathrm{Pr}^{-1/3}}{f\,\mathrm{Re}}=\frac{1}{A_c^2}\left[\frac{\dot{m}\alpha A\,\mathrm{Pr}^{2/3}}{2\rho c_p\Delta p}\right]. \qquad (3)$$

This criterion for assessment of extended surfaces (Fig. 12) clearly shows that the plates with deeper grooves (higher *b/l*) are less "good" from a thermal-hydraulic point of view, but offer a possibility for more compact design as indicated by Fig. 10. In this particular case, the plate with *b/l*=0,4 should be avoided as it has lower thermal performance than the plate with *b/l*=0,5 but similar pressure drop per unit length and consequently lower *j/f* factor. The same applies for the plate with *b/l*=0,14 at the angles higher than β=45° and *Re*=2000 as presented in Fig. 9. A careful optimization process is therefore needed at a design stage to relate *b/l* and angle at a certain flow regime in order to obtain the desired thermal capacity having minimized pressure drop. For this reason more experimental work is required to obtain correlations for heat transfer and pressure drop as a function of flow and geometric parameters. In this context the H. Martin's semi-empirical correlation described in [21] should be mentioned. This equation is based on the Lévêque solution for thermodynamically developing flow and uses superposition of the longitudinal and furrow components incorporated into the friction factor. The equation, beside the extensive experimental methods, might be useful tool in preliminary calculation of the performances as a function of *b/l*, angle β and *Re*.

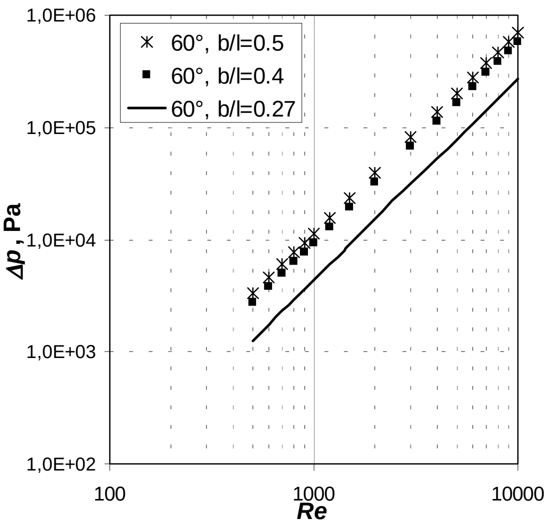

Figure 11. Pressure drop in the chevron channels with identical angle β and projected length at different aspect ratios b/l, calculated using experimental data reported in [13]
Slika 11. Pad tlaka u V-kanalima s identičnim kutem β i projiciranom duljinom pri raznim omjerima b/l, izračunato iz eksperimentalnih podataka iz [13]

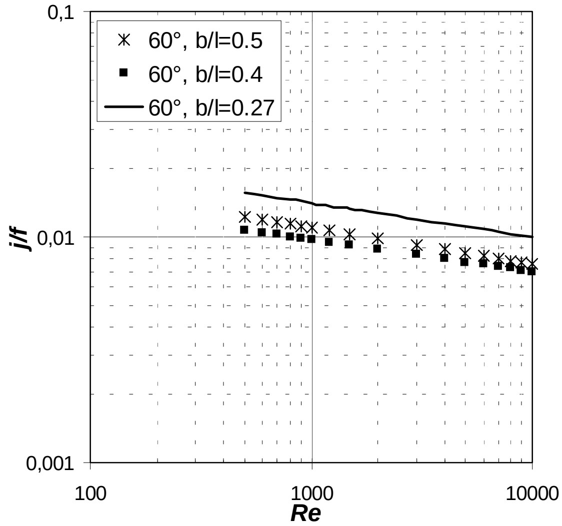

Figure 12. Evaluation of the plate performances in terms of the area goodness factor j/f, Calculated using experimental data reported in [13]
Slika 12. Vrednovanje karakteristika ploče uz pomoć faktora dobrote površine j/f, Izračunato iz eksperimentalnih podataka iz [13]

5 Conclusion
Zaključak

A number of visualization tests have been carried out on two corrugated channels with β=28° and β=61° at low Re-number flow regime in order to support the analysis of influence of different geometric parameters on the channel thermal-hydraulic performances. The presented visualization test results indicate the presence of two flow components occurring simultaneously in both tested channels. The longitudinal component dominates in the flow through the channel with the angle β=61° producing so called wavy longitudinal flow pattern. The flow in the β=28° channel is referred to as criss-cross (furrow) flow, being mainly determined by the furrow component whereby the main part of each substream follows the furrows and change direction at the edges and at the central line of the plate. In general, plates with higher β and *b*/*l* creates channels characterized by more intensive heat transfer and higher pressure drop, probably due to more thorough mixing between the substreams, longer flow path and greater change in momentum. The exception are flows at very low Re-numbers (*Re*<10) when the increase of the angle does not give a rise to the heat transfer coefficient while pressure drop is increased. Also, as Re-numbers are lowered the influence of *b*/*l* on the heat transfer wane.

Furthermore, too high values of β will cause a separation of the longitudinal flow component behind the lee furrow wall side, which will lower heat transfer accordingly. Increase of the flow velocities (Re-number) and *b/l* will lead to the increase of the furrow component. In the flows dominated by the longitudinal component it is believed that this will promote better mixing of two substreams within the cell which explains experimentally observed more intensive heat transfer. In this case, the mentioned separation of the longitudinal stream is expected to have less diminishing influence on the integral heat transfer. Therefore, higher values of *b/l* enable the design of plates with higher angles β i.e. higher thermal performances. Lower *b/l* will increase the influence of the longitudinal component. That might be only desirable for plates with lower angles as it entails better mixing between the two dominant furrow substreams. On the other hand, lowering *b/l* deteriorates heat transfer through the boundary layer between the main furrow component and sinusoidal shaped furrow wall. Because of this counteracting effect, a change of *b/l* is expected to have a limited effect on plates with lower angles unlike the plates with higher angles i.e. with dominant longitudinal component. This is experimentally verified only for the turbulent flow while more investigation is needed in the transient and very viscous flow regimes.

Calculation of the area goodness factor *j/f* indicates higher increase of the pressure drop relative to increase in the heat transfer when plates with deeper grooves i.e. higher *b/l* are used at fixed Re-number and angle. Selection of geometric and flow parameters that would yield highest performances under given pressure drop constraints is, therefore, a very complex issue that requires careful optimization. For this purpose it is essential to correlate dimensionless heat transfer and pressure drop characteristics with the angle, *b/l* and Re-number covering as broad as possible a range of these three parameters by means of either experimental, analytical (e.g. H. Martin's correlation [21]) or numerical methods. The last two can benefit from the information presented concerning the basic flow mechanisms in PHE channels.

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7 Symbols
Oznake

A - developed surface area for heat transfer, *Wb*, m^2
A_c - cross-sectional free flow area, m^2
b - corrugation depth, m
c_p - specific heat capacity, J/(kg·K)
d_h - hydraulic diameter, $2b/\Phi$, m
f - Fanning friction factor, $\Delta p/[4(L/d_h)\rho w^2/2]$, -
j - Colburn factor, $NuPr^{-1/3}/Re$, -
L - developed plate length between ports, m
l - corrugation wave length, m
$\dot{m}$ - mass flow rate, kg/s
Nu - Nusselt number, $\alpha d_h/\lambda$, -
p - corrugation pitch, m
Pr - Prandtl number, $\mu c_p/\lambda$, -
Δp - pressure drop, Pa
$\dot{Q}$ - heat transfer rate, W
Re - Reynolds number, $w d_h \rho/\mu$, -
u - velocity of substream in a furrow, m/s
W - plate width, m
w - mean velocity, $\dot{m}/(A_c\rho)$, m/s
α - heat transfer coefficient referred to developed surface area, $W/(m^2 K)$
β - corrugation inclination angle relative to vertical direction, °
Φ - enhancement factor (ratio developed/projected heat transfer surface area), -
λ - thermal conductivity, W/(m·K)
μ - dynamic viscosity, $N \cdot s/m^2$
ρ - density, kg/m^3

Subscripts
b/*l* - plate with certain aspect ratio b/l

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