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Prenos toplote v toku ledene brozge

Heat Transfer in an Ice-Slurry Flow

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Ledena brozga je do okolja neškodljiva snov, katere uporaba je zaradi njenih dobrih toplotnih lastnosti primerna v mnogih sistemih hlajenja. Do pred nekaj leti so sistemi z ledeno brozgo bili omejeni le na živilsko proizvodnjo, kjer zaradi strupenosti drugih hladiv, uporaba le-teh ni dovoljena. Zaradi hitrega razvoja takšnih sistemov in mnogih inovacij v hladilni tehniki, pa je njihova uporaba mogoča tudi na drugih področjih, na primer daljinsko hlajenje. V ta namen je treba opraviti še veliko raziskav, predvsem eksperimentalnih, saj je analitičen postopek obravnave problema precej zapleten.

Prispevek obravnava rezultate raziskave prenosa toplote v toku ledene brozge znotraj pravokotnega kanala. Na začetku je podan opis preizkusne proge in samega preizkusa, s katerim smo določili intenzivnost prenosa toplote. Dobljeni rezultati so v nadaljevanju razloženi in predstavljeni v diagramih ter primerjani s korelacijami in rezultati meritev drugih avtorjev. Opisan je tudi numerični program, na podlagi katerega je v nadaljevanju narejena primerjava numeričnih in eksperimentalnih rezultatov. Na koncu so narejene še ugotovitve in sklepi raziskave.

(Ključne besede: brozga ledena, prenos toplote, profili temperaturni, programi numerični)

An ice slurry is a harmless substance that can be used in various cooling systems because of its good thermal properties. Until recently, systems with ice slurries were limited to food processing, where conventional, harmful refrigerants are not allowed. The rapid development of such systems and the many innovations in refrigeration have paved the way for ice-slurry systems to be used in other areas, e.g., district cooling. However, a lot of research remains to be done, especially experimental work.

This paper deals with the research results from heat transfer in an ice-slurry flow within a rectangular channel. First, the basics of heat transfer in an ice slurry are explained. Next the experiment to determine the intensity of the heat transfer is explained. Later, the results are explained, and together with the results of some other experiments, shown in diagrams for comparison. In the second part of the paper a numerical program is described; this was used to compare numerical and experimental data. Finally, conclusions from the comparison between the experimental and numerical results are given and discussed.

(Keywords: ice slurry, heat transfer, temperature profile, numerical programs)

0 UVOD

Vse od protokolov, sprejetih v Kyotu in še pred tem v Montrealu, se je v svetu kazala potreba po zmanjšanju uporabe hladiv CFC, predvsem zaradi njihovega škodljivega delovanja na ozračje. Ena izmed možnosti je omejitev hladiv CFC na samo proizvodnjo hladu, medtem ko sta prenos in uporaba hladu opravljena z uporabo drugih snovi. Ena takšnih je ledena brozga, ki je do okolja neškodljiva snov, saj je sestavljena iz vode in ledu ter dodatka, po navadi je to kar sol, alkohol ali kakšna druga snov, ki v

0 INTRODUCTION

Since the protocols in Montreal and later in Kyoto, there has been an urgent need to limit use of CFC refrigerants because of their harmful effect on the atmosphere. One way to do this is to use CFC refrigerants only for cold production, while the transport and usage of cooling energy can be done with other substances. One such substance is a slurry of ice, which is ecologically harmless because it consists only of water, ice and an additive such as salt, alcohol or another substance that lowers the freezraztopini z vodo zniža temperaturo ledišča ledene brozge. Tako lahko dosežemo večje temperaturne razlike v prenosniku in s tem manjše izmere sistema ter nižje temperature hlajenja. Poleg tega pa ima ledena brozga še eno dobro lastnost; zaradi vsebnosti delcev ledu, ima namreč večjo toplotno zmogljivost kot pa sama raztopina, kakor občutno zmanjša investicijske in obratovalne stroške.

Seveda pa se pri uporabi ledene brozge pojavljajo tudi problemi. Pri tem moramo omeniti predvsem dva, stratifikacijo in združevanje delcev ledu v večje kose po določenem času. Stratifikacija je ločevanje dveh komponent zaradi sile vzgona. Pri ledeni brozgi je led lažji od raztopine, zato se ob neustreznem mešanju ustvarita dve plasti, kar lahko občutno poslabša tokovne razmere, v skrajnem primeru pa povzroči tudi zamašitev elementov in ustavitev sistema. Zato je nujno, da se ledena brozga uporabi v čim krajšem času ter da se v elemente sistema (hranilnik, cevovodi itn.) vgradijo mešalne naprave, kar pa lahko slabo vpliva na celoten sistem.

ing temperature of the solution. This way we can have lower cooling temperatures and higher temperature differences inside the heat exchanger, and thus a system with smaller dimensions. Ice slurries also have another good property: because they contain ice particles they have a higher heat capacity as the solution itself, which again lowers the investment and the running costs.

There are, however, also some problems associated with ice-slurry systems. Two are particularly important: stratification and the unification of ice particles after a certain time. Stratification is the separation of two phases due to a buoyancy force. In ice slurries the ice is lighter than the rest of the solution, and so in the case of improper mixing we get two phases, which causes an increase in the pressure drop or even stoppage of the flow and the whole cooling system. To prevent this it is necessary to use an ice slurry a short time after its production and to install mixing elements in the ice-slurry storage and pipes, which can have a negative impact on the whole system.

1 TEORIJA PRENOSA TOPLOTE V LEDENI BROZGI

1 THE THEORY OF HEAT TRANSFER IN AN ICE SLURRY

Pri obravnavanju prenosa toplote v ledeni brozgi sta pomembna predvsem dva mehanizma; prevod toplote in prestop toplote. Matematično lahko prevod toplote zapišemo s Fourierjevim zakonom [1]:

Two mechanisms are important when dealing with heat transfer in ice slurries: heat conduction and heat convection. Heat conduction can be written with Fourier's law [1]:

$$\bar{q} = \frac{\dot{Q}}{\bar{A}} = -\lambda(T)\, gradT \qquad (1),$$

medtem ko lahko prestop toplote opišemo z Newtonovim zakonom hlajenja:

while heat convection is described with Newton's law of cooling:

$$q = \alpha \quad (T_w - T_f) \qquad (2)$$

kjer je $(T_w - T_f)$ temperaturna razlika med tekočino (prosti tok) in površino stene. Seveda je zapis enačbe (2) samo osnovna oblika, saj v dejanskih razmerah nimamo stalnih temperatur ali toplotnega toka. Obe veličini se vzdolž toka spreminjata. Skupno toplotno moč lahko tako zapišemo v obliki integrala lokalnega toplotnega toka q_x vzdolž površine A:

where $(T_w - T_f)$ is the temperature difference between the free flow of the fluid and the surface of the wall. Equation (2) is, of course, just the basic form of the law, since in real problems we do not have constant temperatures or constant heat flux, they both vary along the length of the flow. Thus, we have to write the combined heating power as an integral of q_x along the area A:

$$\dot{Q} = \int_A q_x dA \qquad (3).$$

Pri prestopu toplote je zelo pomembno tudi poznavanje temperaturne in hitrostne mejne plasti ter predvsem tokovnega režima (turbulentni ali

When dealing with heat convection we have to be familiar with the temperature and the velocity boundary layers, and especially with the type laminarni tok). Turbulentni tok zaznamuje zelo neurejeno trirazsežno gibanje razmeroma velikih delov tekočine, kar povzroči povečanje tlačnega padca in intenzivnost prenosa toplote.

Glede na pretekle preizkuse, ki so jih opravili različni avtorji, lahko sklepamo, da ima, poleg hitrosti tekočine in premera cevi, pomemben vpliv na prenos toplote tudi koncentracija delcev ledu v ledeni brozgi. Christensen [2] je ugotovil, da se intenzivnost prenosa toplote zvečuje s povečano koncentracijo ledu. Seveda pa je primerno povečevati koncentracijo ledu samo do neke vrednosti, saj se pri večjih koncentracijah padec tlaka v prenosniku zelo poveča, hkrati pa se povečuje nevarnost stratifikacije toka. Ker želimo v sistemu imeti čim manjši tlačni padec ob čim večjem prenosu toplote, je nujno, da s preizkusi določimo čim boljše razmerje med obema.

of flow (turbulent or laminar). Turbulent flow is characterized as the very disordered three-dimensional motion of a relatively large portion of fluid that causes a greater pressure drop and heat transfer.

We can conclude from previous experiments made by other authors that the heat transfer in an ice slurry is not influenced only by velocity and the diameter of the pipe, but also by the ice-particle concentration. Christensen [2] found that the heat transfer increases with increasing ice-particle concentration up to a certain point, while increasing it beyond that point is pointless due to an increased pressure drop. Since we want to have, at the same time, a low pressure drop and a high heat transfer, we need to find the optimum point with an experiment.

2 OPIS PREIZKUSA

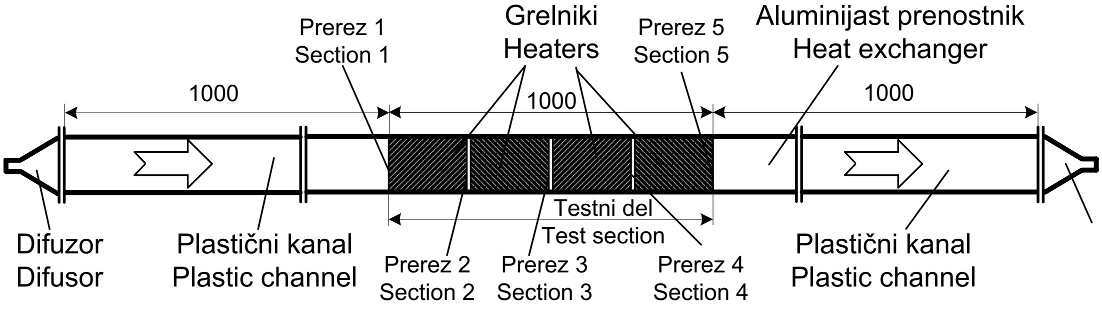
Namen preizkusa je bil določiti intenzivnost prenosa toplote ledene brozge znotraj pravokotnega kanala ter rezultate primerjati z že znanimi podatki za okrogle cevi. Pravokotna oblika prenosnika je bila izbrana zaradi podobnosti z obliko prenosnikov v dejanskih sistemih. Kot osnovni parameter je bil izbran hidravlični premer kanala, ki je znašal 23 mm – enako kakor je bil premer cevi v prejšnjih rezultatih [3]. Zaradi želje po čim bolj intenzivnem prenosu toplote med ledeno brozgo in steno prenosnika je bilo izbrano večje razmerje med širino (126,6 mm) in višino kanala (12,7 mm). Izbrano razmerje je bilo približno 10. Pri tem pogoju smo imeli večjo površino za prenos toplote ter hkrati še vedno ugodne hidravlične razmere.

Testni del prenosnika z dolžino 1 meter je bil izdelan iz aluminijeve zlitine ter razdeljen na 4 odseke po 250 mm, na katere so bili nameščeni električni grelniki (skupaj 8 grelnikov – zgoraj in spodaj), vsak z močjo 1,1kW. Na začetku (prerez 1), koncu (prerez 5) in med vsakim segmentom prenosnika (prerezi 2, 3 in 4) so bila nameščena temperaturna (termoelement: Roth+Co. AG Tip T040, razred A, točnost: ±0,5°C) ter tlačna (Huba Control) zaznavala, skupaj tako na petih mestih (sl. 1). Po dve temperaturni zaznavali sta bili postavljeni na vsakem prerezu, in sicer, 35mm od sredine kanala. Tako je bilo mogoče določiti razvoj temperaturnega in tlačnega profila vzdolž prenosnika. Vsak temperaturni profil je bil izmerjen z dvema zaznavaloma, vendar ne naenkrat. Medtem so vsa druga zaznavala bila odstranjena iz kanala. Tako ni bilo vpliva preostalih zaznaval na izmerjeno temperaturo.

2 DESCRIPTION OF THE EXPERIMENT

The objective of the experiment was to determine the intensity of the heat flux in an ice slurry within a rectangular channel and to compare the results with some other experiments. We chose a rectangular channel because of the similarity with the shape of real heat exchangers. As the main parameter, we chose a hydraulic diameter of 23 mm, the same as the diameter in previous experiments [3]. We chose higher ratio (~10) between the width (126.6 mm) and height (12.7 mm) of the channel in order to have a higher heat transfer from the wall to the ice slurry. This way we had a larger area for the heat transfer and maintained favourable flow conditions.

The test section of the exchanger was 1 metre long and made of aluminium alloy. It was divided into four segments of 250 mm, on which electrical heaters (a total of eight – top and bottom) were installed, each of 1.1kW. At the beginning (cross-section 1), end (cross-section 5) and between each segment (cross-section 2, 3 and 4), temperature (Roth+Co. AG Type T040, Class A, accuracy: ±0,5°C) and pressure (Huba Control) sensors were installed. Two temperature sensors were installed for every section, each 35mm away from the middle of the channel. In this way we were able to measure the pressure drop and the temperature at five points along the channel and thus determine the development of the temperature and the pressure-drop profiles. Each temperature profile was measured with two sensors, but only one at a time, while all the other sensors were removed from the channel. In this way the measured temperature was not influenced by any other sensor.



Sl. 1. *Shema prenosnika*
Fig. 1. *Heat-exchanger scheme*

Pred prenosnikom in za njim sta bila nameščena en meter dolga plastična kanala enakega prereza, ki bi naj zagotovila, da na testnem delu prenosnika ni bilo vpliva vstopnega in izstopnega dela prenosnika. Predhodno je bil izdelan tudi poseben pretvornik toka, difuzor, ki je spremenil tok iz okroglega prereza v pravokotni in nazaj.

Meritve so bile opravljene v laboratoriju Inštituta za termodinamiko (Institut de Génie Thermique IGT) na Visoki tehniški šoli (École d'Ingénieurs du Canton de Vaud) v Yverdon-u v Švici. Posebna konstrukcija, krmilni in nadzorni sistem ter cevne povezave so bile narejene za opravljanje meritev na ledeni brozgi [5].

Opravili smo več meritev, pri katerih smo spreminjali toplotni tok (1,8kW/m^2, 7,2kW/m^2), ter masni delež ledu (15 do 20 masnih %), medtem ko smo preostale parametre (masni pretok $\dot{m}$ = 1,2kg/s; vstopna temperatura brozge – T_{in} = -3,2°C ± 0,1; Re = 5100 do 5200) poskušali vzdrževati čim bolj stalne. Kot dodatek smo uporabili propilen glikol (10 masnih %).

3 REZULTATI MERITEV

Z meritvami smo dobili temperaturne profile na določenem prerezu vzdolž prenosnika toplote (slika 2), iz katerih smo nato lahko določili intenzivnost prestopa toplote v ledeni brozgi. Zaradi rahlega nihanja vstopne temperature ledene brozge v času opravljanja ene meritve smo za predstavitev razvoja temperaturnega profila (sl. 2) uporabili tako imenovano skaliranje, ki izniči vpliv spremenljivosti vstopne temperature. Pri tem uporabimo naslednjo enačbo, kjer y pomeni razdaljo od sredine kanala ter x lego vzdolž kanala:

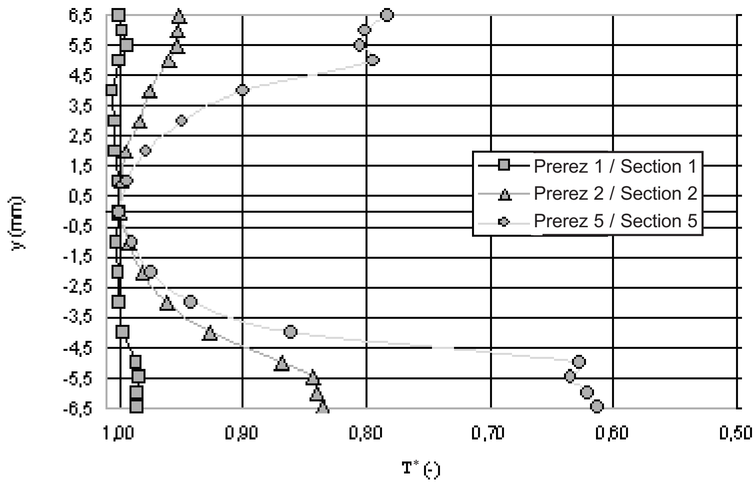
Before and after the heat exchanger, one metre long, plastic channels of the same cross-section were installed in order to prevent any influence of the entrance or exit part from reaching the test section. A special diffuser was also made to transform the flow from the cylindrical pipe to the rectangular channel.

Measurements were made in a laboratory at the Institute for Thermodynamics (Institut de Génie Thermique IGT - École d'Ingénieurs du Canton de Vaud) in Yverdon, Switzerland. A special construction, control systems and piping were made for the purpose of ice-slurry measurements [5].

Measurements were made with a variable heat flux (1.8kW/m^2, 7.2kW/m^2) and a concentration of ice particles (15–20 mass %), while we tried to keep the other parameters (mass flow $\dot{m}$ = 1.2kg/s; entrance temperature T_{in} = -3.2°C ± 0.1; Re = 5100 dto 5200) more or less constant. The additive used was propylene glycol (10 mass %).

3 RESULTS OF THE MEASUREMENTS

With the experiment we obtained temperature profiles at certain sections along the channel (Figure 2), which were further used to determine the intensity of the heat transfer in the ice slurry. Because of slight oscillations of the ice slurry's entrance temperature during the measurements we had to use a so-called "scaling" method (non-dimensionalising), which nullifies those oscillations, to show the development of the temperature profiles along the channel (Figure 2). To do so we used the following equation, where x represents the position along the length of the channel and y, the distance from the middle of the channel:



Sl. 2. *Temperaturni profili*
Fig. 2. *Temperature profile*

$$T^* = \frac{T(x,y)}{T(x,0)} \quad (4).$$

Brezrazsežna temperatura T^* (slika 2) pomeni relativno spremembo temperature tekočine *T(x,y)* na različnih prerezih vzdolž kanala glede na temperaturo v sredini kanala *T(x,0)*.

Iz dobljenih podatkov lahko določimo lokalno Nusseltovo število po enačbi [3]:

The dimensionless temperature T^* (Figure 2) represents a relative change of the fluid temperature *T(x,y)* compared with the temperature at the middle of the channel *T(x,0)* at different sections along the channel.

From the obtained data we are able to determine the local Nusselt number according to Equation [3]:

$$Nu_x = \frac{\alpha_x \cdot D_h}{\lambda} \quad (5),$$

kjer se lokalna toplotna prestopnost α_x določi kot:

where the local convective coefficient α_x is calculated as:

$$\alpha_x = \frac{q}{T_{w,x} - \overline{T}_{f,x}} \quad (6)$$

in je $T_{w,x}$ temperatura stene na dolžini *x* in $\overline{T}_{f,x}$ povprečna temperatura tekočine na dolžini *x*, ki se izračuna kot:

$T_{w,x}$ is the temperature of the wall at the length *x* and $\overline{T}_{f,x}$ is the average temperature of the fluid at the length *x*, which can be calculated as:

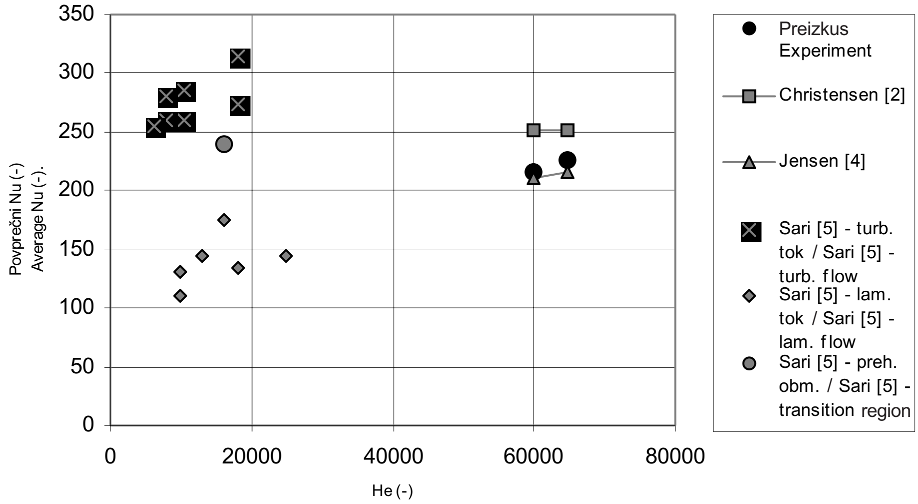
$$\overline{T}_{f,x} = \frac{1}{\overline{v}_f \quad H} \int_{-y}^{y} v_x(y) T(y) dy \quad (7).$$

Kjer je $\overline{v}_f$ povprečna hitrost tekočine v kanalu in $v_x(y)$ hitrostni profil tekočine po višini (os *y*).

Z integriranjem lokalnega Nu števila vzdolž prenosnika pa dobimo povprečno Nu število. Dobljeno povprečno Nu število smo v odvisnosti od Hedstromovega števila primerjali z dvema korelacijama ([2], [4]) in rezultati meritev, ki jih je opravil Sari [5] (sl. 3). He število izraža razmerje med kritično strižno napetostjo ter silo viskoznosti in je

where $\overline{v}_f$ is the average velocity of a fluid and $v_x(y)$ is the velocity profile along the height of the channel (y-axis).

With integration of the local Nu number along the channel we obtain the average Nu number, which we compared with two correlations ([2], [4]) and with the results of an experiment by Sari [5] (Figure 3). The results are compared using the Hedstrom number (He), which expresses the ratio of the critical shear stress



Sl. 3. *Primerjava rezultatov preizkusa z rezultati nekaterih drugih avtorjev*
Fig. 3. *Comparison of the results from our experiment with the results of other authors*

pri ledeni brozgi predvsem funkcija masnega deleža ledu. Definirano je kot:

and the viscous forces between the particles of the fluid. In the case of ice slurries the number mainly a function of the ice concentration. It is defined as:

$$He = \frac{\tau_0 \cdot D^2 \cdot \rho}{\eta^2} \qquad (8).$$

Kakor je razvidno (sl. 3), so naši rezultati podobni korelacijam, ki sta jih podala Christensen [2] in Jensen [4] na podlagi preizkusov. V diagram smo dodali tudi rezultate meritev, ki jih je opravil Sari [5], saj so rezultati njegovih meritev na neki način primerljivi z našimi. Če pogledamo enačbo za določitev He števila, vidimo, da imamo v imenovalcu dinamično viskoznost, ki je za ledeno brozgo s propilen glikolom (uporabljena pri naših meritvah) približno za razmerje 8 manjša od dinamične viskoznosti ledene brozge z etanolom, ki jo je uporabil Sari [5]. Zato je tudi He število sorazmerno manjše, medtem ko je vrednost povprečnega Nu števila primerljiva z našimi rezultati.

Hkrati smo lahko iz rezultatov meritev ugotovili, da smo kljub uporabi mešalnih elementov imeli prisotno stratifikacijo (ločevanje komponent) tekočine. Na to nakazujeta različni temperaturi blizu stene, zgoraj in spodaj (sl. 2 in 4).

From Figure 3 we see that our measurements yielded similar results to the correlations proposed by Christensen [2] and Jensen [4]. The results from Sari [5] are also added to Figure 3, since it is clear that his results yield similar results to our own. If we look at the equation for He number we see that we have a dynamical viscosity in the denominator of the equation. The viscosity of the ice slurry with propylene glycol is approximately eight times lower than the viscosity of the ice slurry with ethanol, which was used by Sary [5]. This is the reason why we had higher He numbers than Sari [5], while his average Nu number was similar to our results.

In results also showed that we had stratification present inside the channel even though we used mixing elements. Different temperatures at the top and the bottom wall indicate this (Figs. 2 and 4).

4 NUMERIČNI PROGRAM

V okviru projekta smo dobljene preizkusne podatke tudi preverili z uporabo numeričnega programa, ki ga je sestavil P. Egolf in dopolnil A. Kitanovski ter je napisan v programskem jeziku Delphi. Teoretično ozadje programa za okroglo cev

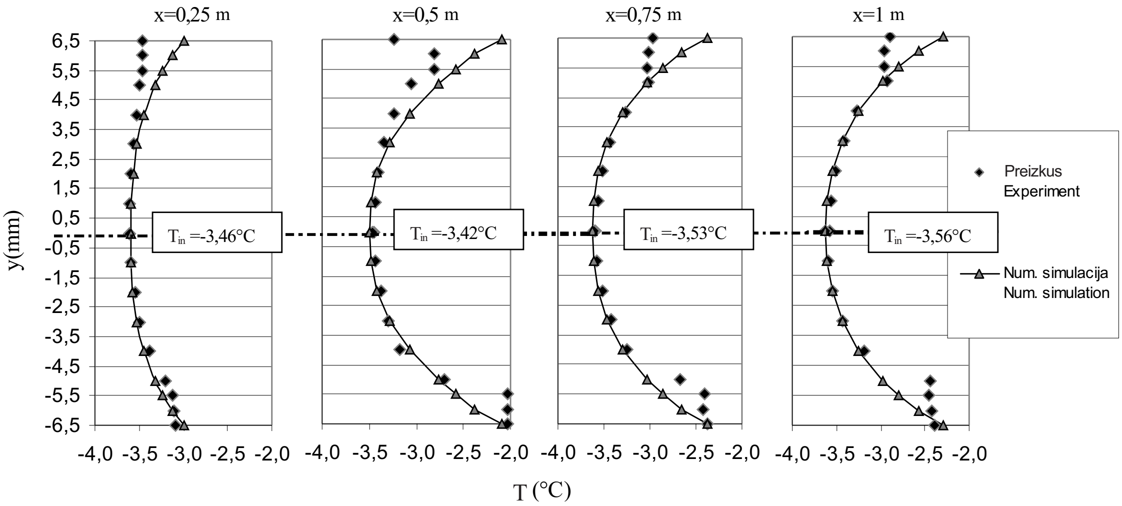
4 NUMERICAL PROGRAM

The experimental results were verified with a numerical program designed by P. Egolf [6] and upgraded by A. Kitanovski in the Delphi programming language. The theoretical part of the programme was written by Egolf [6] for a pipe, while we adapted the je v celoti opisal Egolf [6], medtem ko smo ga v skladu z našim problemom priredili za pravokotni kanal [3]. Program je bil izpeljan iz osnovnih hidrodinamčnih enačb (energijska, kontinuitetna in gibalna), ob upoštevanju robnih in začetnih pogojev ter enačb za popis hitrostnega profila za Binghamovo tekočino. Program upošteva dejstvo, da je hitrostni profil že razvit, medtem ko se temperaturni profil šele razvija.

Iz numerične simulacije za model laminarnega toka smo opazili, da dobimo drugačne rezultate kakor iz preizkusa [3], kar dokazuje, da smo kljub vsemu v kanalu imeli turbulentni tok. Zato smo v nadaljevanju upoštevali, da imamo v toku tudi turbulentno termično difuzivnost, kar se je izkazalo za mnogo ustreznejše (sl. 4).

programme for a rectangular channel according to our problem [3]. The programme was derived using three basic equations (energy, momentum and continuity) with consideration of equations for the velocity profile of Bingham fluids and the initial/boundary conditions. Within the numerical model we considered the fact that the velocity profile was fully developed, while the temperature profile was still developing.

From a simulation of the laminar flow we determined that the numerical results are totally different from the ones we obtained from the experiment [3], which proves that we did not have laminar flow, but rather transient or turbulent flow. Thus, we used turbulent thermal diffusivity in our programme, which proved correct since the results were a lot better (Figure 4).



Sl. 4. *Primerjava eksperimentalno in numerično dobljenih temperaturnih profilov*
Fig. 4. *Comparison of the results from the numerical simulation and experiment*

Kakor je razvidno s slike 4, smo blizu stene dobili nepričakovan potek temperaturnih profilov. Po analizi vseh možnih razlag smo prišli do sklepa, da je takšen potek mogoče razložiti na dva načina. Prvo razlago lahko opredelimo kot napako merjenja, zaradi neprimernosti uporabljenih zaznaval ali pa zaradi nenatančnosti pri določitvi odmikov. Glede na uporabljene merilne metode je ta razlaga manj verjetna. Zaradi pomanjkanja časa je bil posamezen temperaturni profil izmerjen le dvakrat v dveh urah. Oba rezultata meritev sta bila primerjana in sprejeta za pravilna, če je bila razlika med njima manjša od izračunane standardne negotovosti meritve (za termoelement z natančnostjo ±0,5°C (navedena od proizvajalca) znaša standardna negotovost 0,3°C).

As we can see from Figure 4, we obtained some unexpected results (near the wall) for the temperature profiles. After analyzing all the possible causes of such course of temperature profiles, we came down to two possibilities. First of all, we can declare it as an error of measurements due to improper sensors or an inaccurate measurement of the sensor-position deviations. Due to the measuring techniques and devices used, this reason is less likely to be the cause. Because of a tight time schedule, each temperature profile was measured only twice, with a time delay of about 2 hours. Both results were compared and accepted as correct if the difference between them was less than the calculated standard uncertainty (for a thermocouple with

Če sta meritvi bili sprejeti kot pravilni, smo v nadaljevanju za izračun uporabili njuno povprečno vrednost.

Druga, bolj verjetna razlaga temelji na dejstvu, da je prišlo do lokalne spremembe tokovnega režima. Iz diagrama odvisnosti kritičnega Re števila in He števila za ledeno brozgo s propilen glikolom [3] lahko ugotovimo, da smo glede na naše podatke bili v bližini prehodnega območja. Zato je mogoče, da je blizu stene prišlo do taljenja delcev ledu in tako do lokalne spremembe transportnih lastnosti tekočine, kar je povzročilo spremembo tokovnega režima. Zato bi bilo treba opraviti dodatne meritve, s katerimi bi lahko natančneje ugotovili, kaj je razlog takšnih potekov temperaturnih profilov v bližini stene.

S spreminjanjem vrednosti turbulentne toplotne difuzivnosti smo poskušali dobiti čim boljše ujemanje med rezultati meritev in numerične simulacije. Pri tem smo prišli do ugotovitve, da se turbulentna toplotna difuzivnost vzdolž toka zmanjšuje (sl. 5), kar je bil vsekakor nepričakovan rezultat, saj bi morala toplotna difuzivnost v primeru dobro razvitega toka biti skozi celoten prenosnik bolj ali manj nespremenljiva oziroma se kvečjemu povečevati.

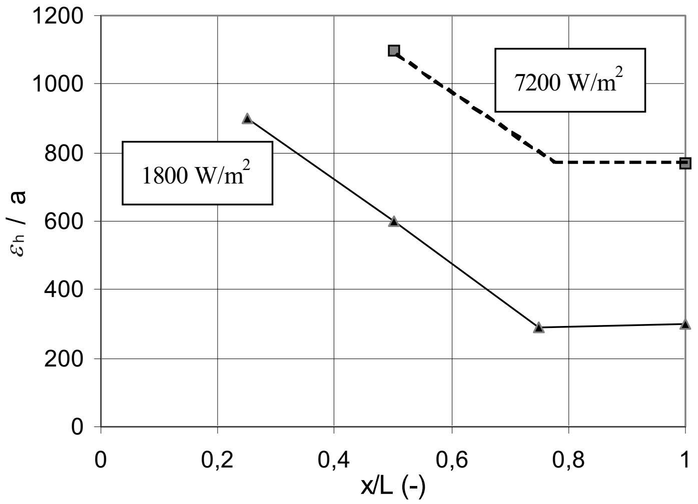
Razlog za takšen potek toplotne difuzivnosti je bil v sami konstrukciji prenosnika. Difuzorja, ki sta bila nameščena pred prenosnikom toplote in za njim, sta namreč imela kot razširitve približno 20°, kar je občutno preveč glede na nekatere priporočene vrednosti (približno do 12°). Zaradi prehitre razširitve toka je v pretvorniku prišlo do močnega turbulentnega gibanja, ki se je nadaljevalo

an accuracy of ±0.5°C (stated by manufacturer) the calculated standard uncertainty is 0,3°C). If accepted, the average of both results was later on used in the calculations.

The second explanation is based on the fact that there were some local changes of flow type near the wall. If we check the dependency of the critical Re number and the He number [3], which tells us what type of flow we have, we see that we were close to the transient area between laminar and turbulent flow. So, it is possible that close to the wall, where the ice particles were melting, a change of flow type occurred due to a local change of the transport properties of the fluid. It would be necessary to perform more experiments relating to this issue to determine the true cause of such temperature profiles.

With the numerical programme we tried to achieve the best agreement between the numerical and experimental results by changing the value for the turbulent thermal diffusivity. We found that the value of the turbulent thermal diffusivity along the channel was decreasing (Figure 5), which was also unexpected since it should be more or less constant or at the utmost slightly increasing.

After evaluating this result we found that the reason for decreasing the thermal diffusivity along the channel was the construction of exchanger. The angle at which the flow was transformed from circular to rectangular in the diffuser was about 20°, which is too high according to some recommendations (up to ~ 12° is recommended). Because of this quick change of flow, strong turbulent motion ap-



Sl. 5. *Razmerje turbulentne ε_h in laminarne toplotne difuzivnosti vzdolž prenosnika toplote*
Fig. 5. *Dependency of turbulent ε_h and laminar a thermal diffusivity along the exchanger*

tudi v samem prenosniku toplote in se šele proti koncu prenosnika umirilo.

5 SKLEPI

Večina preizkusov, ki so bili opravljeni na temo prenosa toplote v ledeni brozgi, je bilo narejeno z okroglimi prenosniki toplote (cevi), zato je v svetu na voljo malo rezultatov, pri katerih je bil uporabljen pravokotni prenosnik toplote. Hkrati pa je zaradi podobnosti z dejanskimi sistemi primernejši od okroglih prenosnikov toplote.

Iz rezultatov meritev smo lahko ugotovili, da smo kljub uporabi mešalnih elementov imeli stratifikacijo tekočine. Hkrati pa smo ugotovili, da smo blizu stene dobili nepričakovane poteke temperaturnih profilov, ki so najverjetneje posledica lokalnih sprememb lastnosti tekočine in s tem tokovnega režima. Pri primerjavi rezultatov preizkusa in numeričnega programa pa smo prišli do sklepa, da smo v kanalu imeli turbulentni, slabo razvit tok tekočine zaradi prevelikega kota razširitve pri difuzorju. Zato bi v prihodnje bilo nujno preveriti te rezultate z difuzorjem, ki bi imel manjši kot razširitve.

Primerjava rezultatov, dobljenih z našimi meritvami, in rezultatov drugih avtorjev je pokazala, da smo se pravilno lotili problema, saj so iz meritev izračunane vrednosti za Nu število primerljive z rezultati drugih avtorjev.

peared, which continued along the exchanger and was smoothed only by the end of the exchanger.

5 CONCLUSIONS

Most of the experiments relating to heat transfer in ice slurries were made with cylindrical exchangers (pipes), thus there are not many results available where rectangular channel is used. At the same time a rectangular channel is more like the heat exchangers in real systems than a cylindrical one, and thus of greater interest.

From the experiment we found that even though mixing elements were installed in the system, we still had stratification (separation of fluid components) present. We also obtained some unexpected temperature profiles, which are most likely the result of local changes in the fluid transport properties and thus the flow type. When we compared the results of the experiment and the numerical programme we came to a conclusion, that we had turbulent, undeveloped flow because of a too large angle widening in the diffuser. It would be necessary to perform more experiments with a new diffuser to determine the appropriate heat transfer in ice slurries.

The results of our experiment and those from other experiments are very similar, which proves that we used an appropriate approach to the problem.

6 OZNAKE
6 NOMENCLATURE

površina	A	m^2	area
premer	D	m	diameter
višina kanala	H	m	height of the channel
Hedstromovo brezrazsežno št.	He	-	Hedstrom dimensionless number
masni pretok	$\dot{m}$	kg/s	mass flow
Nusseltovo brezrazsežno št.	Nu	-	Nusselt dimensionless number
gostota toplotnega toka	q	W/m^2	heat flux density
toplotna moč	$\dot{Q}$	W	heating power
Reynoldsovo brezrazsežno št.	Re	-	Reynolds dimensionless number
temperatura	T	°C	temperature
brezrazsežna temperatura	T^*	-	dimensionless temperature
hitrost	v	m/s	velocity
položaj vzdolž toka	x	m	position along the channel
razdalja od sredine kanala	y	m	distance from the middle of channel
toplotna prestopnost	α	W/m^2K	convective heat-transfer coefficient
toplotna prevodnost	λ	W/mK	conductive heat-transfer coefficient
dinamična viskoznost	η	kg/ms	dynamical viscosity
gostota	ρ	kg/m^3	density

strižna napetost	τ	Pa	shear stress
Indeksi			**Subscripts**
tekočina	f		fluid
hidravlični	h		hydraulic
vstop	in		entrance
lokalno	x		local
stena	w		wall
kritično	0		critical

7 LITERATURA
7 REFERENCES

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