Chemical and Process Engineering 2013, 34 (1), 5-16
DOI: 10.2478/cpe-2013-0002

# THE EFFECT OF REGULATING ELEMENTS ON CONVECTIVE HEAT TRANSFER ALONG SHAPED HEAT EXCHANGE SURFACES

Jozef Cernecky*, Jan Koniar, Zuzana Brodnianska

Technical University in Zvolen, Faculty of Environmental and Manufacturing Technology, Department of Environmental Technology, Studentska 26, 960 53 Zvolen, Slovakia

The paper deals with a study of the effect of regulating elements on local values of heat transfer coefficients along shaped heat exchange surfaces with forced air convection. The use of combined methods of heat transfer intensification, i.e. a combination of regulating elements with appropriately shaped heat exchange areas seems to be highly effective. The study focused on the analysis of local values of heat transfer coefficients in indicated cuts, in distances expressed as a ratio $x/s$ for 0; 0.33; 0.66 and 1. As can be seen from our findings, in given conditions the regulating elements can increase the values of local heat transfer coefficients along shaped heat exchange surfaces. An optical method of holographic interferometry was used for the experimental research into temperature fields in the vicinity of heat exchange surfaces. The obtained values correspond very well with those of local heat transfer coefficients $\alpha_x$, recorded in a CFD simulation.

**Keywords:** heat transfer, convection, holographic interferometry

## 1. INTRODUCTION

At present, heat transfer enhancement by thermal processes of different technical and technological devices is a dominant topic in terms of maximising the use of energy and therefore saving time and money. Scientists from different countries all around the world dealt and have been dealing with the issue of heat transfer in flat and curved surfaces. Fehle et al. (1995) investigated the local Nusselt numbers from isotherms near a wall via holographic interferometry. They studied two geometries of heat exchange surfaces (arc and rectangular contours) arranged one above the other and in a staggered arrangement at different velocities of the flowing fluid. Heat exchange contours were heated from inside by hot water. Kilicaslan and Sarac (1998) used holographic interferometry in order to determine temperature fields and the distribution of velocities was observed using the LDA (Laser Doppler Anemometry), which is a non-contact optical method for measuring the velocity of flowing fluids. The study was carried out on two different (triangular and arc) contours, in comparison with a smooth contour, in order to enhance heat transfer. The velocity of the flowing fluid was changed in the range from laminar to turbulent flow at a constant temperature of the heated surface. Tauscher (2000) in his dissertation dealt with research into heat transfer using different shapes of regulating and eddy elements for heat transfer enhancement by forced air convection. In his own study he used an optical method of holographic interferometry and the LDA method as well as numerical calculations. He compared parameters such as the size, shape, distance and arrangement of regulating and eddy elements. Herman and Kang (2002) tried to improve heat transfer by adding curved vanes over the edge of a rectangular groove in a heated channel at lower velocities of the flowing fluid. Temperature fields were visualised by means of holographic interferometry. Heat transfer values were compared with a basic grooved

*Corresponding author, e-mail: cernecky@tuzvo.sk

channel without vanes and with a smooth channel without grooves and vanes. Islamoglu and Parmaksizoglu (2003) observed the effect of a channel height on the improvement of heat transfer characteristics. They determined a heat transfer coefficient in forced air convection and a friction coefficient. Measurements were carried out for two different channel heights (5 and 10 mm) at a fixed angle of triangular surface and for different velocities of the flowing fluid. Zhang et al. (2004) numerically simulated forced air convection in a channel with an arc contour of plates at a constant temperature of the channel wall. They investigated the effect of channel geometry and spacing on the structure of created vortexes at different velocities of the flowing fluid in the region of laminar flow. Elshafei et al. (2010) dealt with experimental research on convective heat transfer characteristics and pressure drop by flow in a channel with arc-shaped grooves. The channel wall had a constant temperature and a fixed ratio of the arc surface. The effect of changing flowing fluid velocity and the effect of a groove arrangement (one above the other or staggered) on heat transfer and pressure drop were observed.

Our research is focused on heat transfer intensification on shaped heat exchange surfaces using regulating elements. The local values of heat transfer coefficients were determined in the indicated cuts (Fig. 4a, b) in the distances expressed as a ratio $x/s$ (0; 0.33; 0.66 and 1). Temperature fields in the vicinity of heat exchange surfaces were visualised by holographic interferometry. Demonstrations of CFD simulations are also added in order to supplement the experimental results.

## 2. CONVECTIVE HEAT TRANSFER IN SHAPED HEAT EXCHANGE SURFACES

Forced convection occurs by forced air flow under the influence of external forces acting on the interface of systems, or the forces acting inside the system. It is also accompanied by natural convection. The bigger the difference of temperatures in the system and the smaller the velocity of forced motion, the bigger the relative influence of the natural convection on the forced convection. In the forced convection the air flow is induced artificially – by a fan. The heat transfer coefficient is influenced by the velocity, temperature, air flow properties and the temperature, shape and size of the observed surface. Heat flow density by convective heat transfer from the heated surface into the ambient surroundings is determined from Newton's relation (Bergman et al., 2011; Lienhard IV and Lienhard V, 2006):

$$q = \alpha \cdot \left(T_w - T_\infty\right) \tag{1}$$

where $\alpha$ is the heat transfer coefficient, $T_w$ is the surface temperature, $T_\infty$ is the surrounding temperature.

The intensity of heat transfer from a shaped surface into the fluid (or vice versa) is not the same on the entire body surface. The heat transfer coefficient has different numerical values for different parts of the body surface. In order to characterise the irregularity of heat transfer intensity, the concept of the local heat transfer coefficient $\alpha_x$, is introduced. The local heat transfer coefficient is a parameter which characterises heat transfer intensity on an elementary area of the heat exchange area $dA$:

$$\alpha_x = \frac{d\phi}{\left(T_w - T_\infty\right) \cdot dA} \tag{2}$$

where $\phi$ is the heat flow, $A$ is the heat exchange area.

## 3. VISUALISATION OF TEMPERATURE FIELDS IN THE SURROUNDINGS OF SHAPED HEAT EXCHANGE SURFACES BY HOLOGRAPHIC INTERFEROMETRY

Interferometric methods of the temperature field visualisation belong to the most precise optical methods used to investigate the inhomogeneities of transparent objects. Their advantage is that other particles, which could affect the flow, are not added into the fluid flow. In our research temperature fields in the surroundings of shaped surfaces are visualised via holographic interferometry. Interferometry is based on the principle of measuring a phase shift of beams while passing through an inhomogeneous transparent object. It is possible to visualise a phase shift by means of interference fringes, namely by the comparison of a light beam which passes through the object and the reference light beam (Hauf and Grigull, 1970; Merzkirch, 1974).

A change in the optical path $\Delta o$, of the object light beam compared with the reference light beam which passes through the reference surroundings with a refractive index $n_\infty$, is given by a curve integral along a beam path (Vest, 1979):

$$\Delta o(x,y) = \int_0^L \left[ n(x,y) - n_\infty \right] dz \tag{3}$$

where $L$ is the length of an investigated area along which the light beam (200 mm) passes, $n$ is the refractive index in an investigated area, $n_\infty$ is the refractive index of the ambient surroundings.

The beam path is the function of the searched distribution of the refractive index. The accrued interference is reflected in a holographic interferogram image in the form of interference fringes. For the change of an interference order compared with a reference state, this relation is true:

$$\Delta s\,(x,y) = \frac{\Delta o(x,y)}{\lambda} \tag{4}$$

where $\Delta s$ is the change of the interference order, $\lambda$ is the wavelength of laser radiation (632.8 nm).

For ideal gases the refractive index can be expressed by the Gladstone-Dale relation $n\text{-}1 = K{\cdot}\rho$ according to (Martynenko and Khramtsov, 2005; Pavelek and Štětina, 1997), where $K$ is the Gladstone-Dale constant (for He-Ne laser with a wavelength of 632.8 nm and dry air has a value of $K = 2.2563.10^{-4}$ $m^3$/kg), $\rho$ is the ambient density.

For the refractive index in the investigated area at constant pressure it is true, that (Pavelek et al., 2007):

$$n = 1 + \frac{K}{r} \cdot \frac{p}{T} \tag{5}$$

where $r$ is the gas constant, with a value of 287.04 J/(kg·K) for the air, $p$ is the pressure.

For the refractive index of the ambient surroundings at constant pressure it is true that:

$$n_\infty = 1 + \frac{K}{r} \cdot \frac{p}{T_\infty} \tag{6}$$

Density can be determined from a state equation for the ideal gases (Pavelek et al., 2007):

$$\rho = \frac{p}{rT} \tag{7}$$

After the substitution and modification of the previous relations, a relation for calculating the distribution of temperatures from the distribution of the interference order can be expressed as:

$$T(x,y) = \frac{T_\infty}{1 + \frac{r}{K}\frac{T_\infty}{p_\infty}\frac{\Delta s(x,y)\lambda}{L}} \tag{8}$$

Temperature depends on the state parameters of ambient surroundings, the model´s length, the wavelength and the interference order change.

### *3.1. A holographic variant of the Mach-Zehnder interferometer*

A non-contact optical method of holographic interferometry was used for the temperature field visualisation in the surroundings of shaped heat exchange surfaces. A holographic variant of the Mach-Zehnder interferometer was created (according to Fig. 1) in order to record the images of holographic interferograms of temperature fields.

A He-Ne laser with a wavelength of 632.8 nm was used as a radiation source. A light beam from the laser *L* after the reflection on the mirror $M_1$ was divided into an object beam *o* and a reference beam *r* by a beam splitter *BS.* The object beam was adjusted by means of a system (micro-objective lens $MO_2$, spatial filter $F_1$ and objective lens $O_2$) to a parallel beam with a larger diameter which passed through a measuring space *MS* and fell on a holographic plate *HP*. The experimental apparatus was placed in the focal point of an objective lens $O_3$. The reference beam adjusted by the system (micro-objective lens $MO_2$, spatial filter $F_2$ and objective lens $O_2$) to the parallel beam with a larger diameter was consequently reflected from the mirror $M_3$ and the mirror $M_4$ and it fell on the holographic plate *HP*.

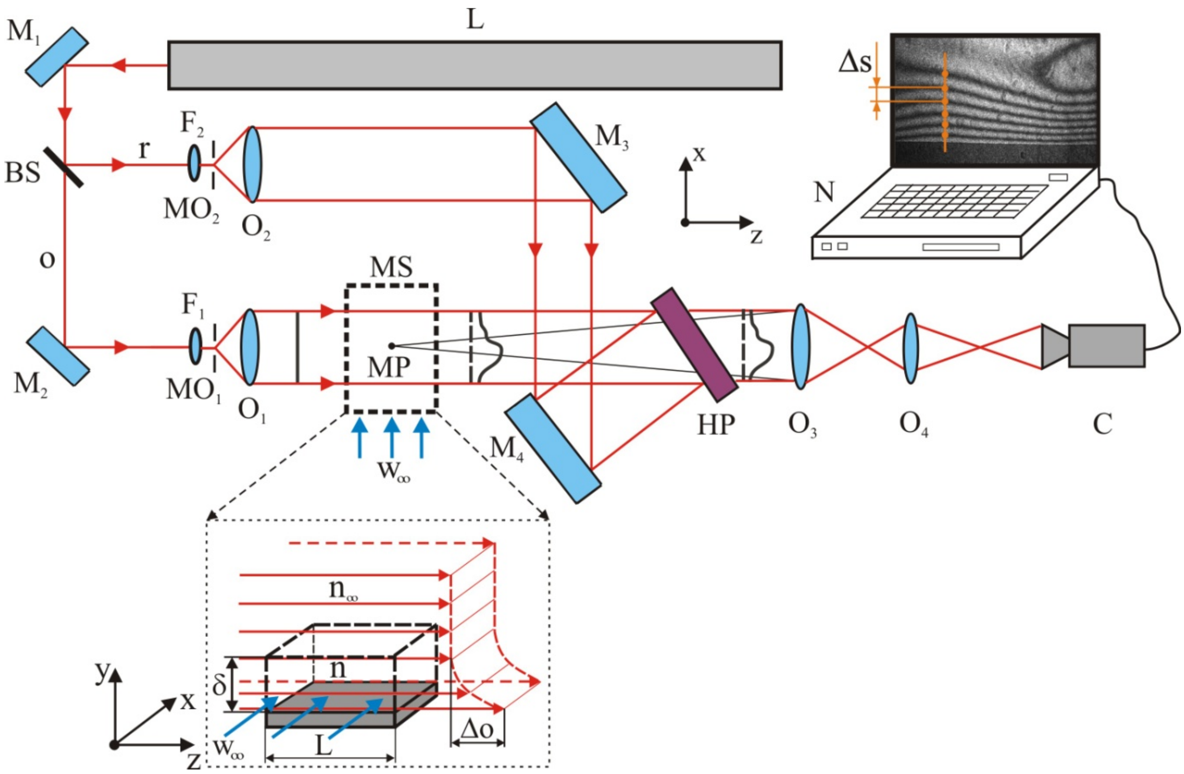


Fig. 1. A holographic variant of the Mach-Zehnder interferometer

A method of real time (a method of active fringes) was used for the visualisation. Both beams of rays were first recorded on a holographic plate without optical inhomogeneities in the measuring space. After the photochemical processing of the holographic plate, the plate was illuminated by a reconstructed beam which should be congruent with the reference beam *r*. The objective lenses $O_3$ and $O_4$ enabled us to record a temperature field image into the *CCD* camera *C*.

### 3.2. Determination of local heat transfer coefficients from interferograms

The calculation of heat transfer from temperature derivations was used in evaluating interferograms. In the flux of the body surface by air with a temperature $T_\infty$, different from a surface temperature $T_x$, at the point *x*, a local heat transfer between the surface and air takes place at this point. The value of the local heat transfer coefficient $\alpha_x$, depends on many factors, for example the flow velocity, the shape of the flux surface, the location of an investigated place and the temperature difference between the surface and ambient surroundings. A typical shape of a temperature contour in the thermal boundary layer with a local thickness $\delta_x$, by laminar flux of the surface with the local temperature $T_x$, higher than the surrounding temperature is shown in Figure 2.

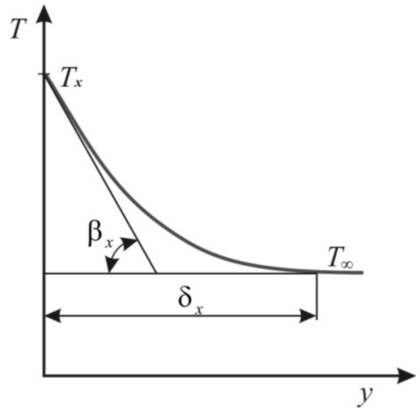


Fig. 2. A temperature contour in the thermal boundary layer by laminar flux of the surface

The local value of the heat transfer coefficient can be calculated from the equation:

$$\alpha_x = -\lambda_{ai}\left(\frac{dT}{dy}\right)_x \frac{1}{T_x - T_\infty} \tag{9}$$

where $\lambda_{ai}$ is the coefficient of the thermal conductivity of air, $T_x$ is the temperature at the point *x*.

From the calculated shape of the temperature contour the temperature difference $(T_x - T_\infty)$ and the temperature derivation are expressed via the angle $\beta_x$, which is created by a tangent to the temperature contour at the surface point with the *y*-axis (Fig. 2). For the temperature derivation at the surface in the direction perpendicular to the surface, it is true that:

$$\left(\frac{dT}{dy}\right)_x = tg(\beta_x) \tag{10}$$

where $\beta_x$ is the angle which is created by the tangent to the temperature contour at the surface point with the *y*-axis.

By substituting Equation (10) into Equation (9) the relation for calculating the local value of heat transfer coefficient is:

$$\alpha_x = -\lambda_{ai} \cdot tg(\beta_x) \cdot \frac{1}{T_x - T_\infty} \tag{11}$$

This method of calculating the heat transfer coefficient from temperature derivations is advantageously applied in heat transfer interferometric research since detailed temperature distribution can be defined from interferograms.

## 4. EXPERIMENTAL RESEARCH OF LOCAL HEAT TRANSFER COEFFICIENTS ALONG THE SHAPED HEAT EXCHANGE SURFACES

In this paper we focused on the effect of regulating elements on heat transfer along heated heat exchange surfaces with forced air convection. The basic geometric arrangement of shaped heat exchange areas is shown in Figure 3. Dimensions of the arrangement of profiled areas including regulating ducts are defined in the figure on the right. Corrugated plates have the same geometry and are placed opposite each other by heat exchange areas. Sensors of surface temperatures which are used for obtaining marginal conditions for interferometric measurements are placed in the plates (Fig. 3). Measurement points are placed symmetrically in the upper and lower plate. Outer parts of heating plates were isolated by thermo-isolating material. The investigated area which was limited by the visual field size according to the objective lens of a measurement branch of the interferometer is shown in the figure on the left.

In order to intensify heat transfer the regulating ducts, which decrease thermal boundary layer thickness and thus local heat transfer coefficients are increased, were put between the heat exchange surfaces. The thermal boundary layer occurs near the wall surface at different wall and fluid temperatures. Changes of fluid temperature occur in the direction perpendicular to the wall surface. The fluid temperature above it is steady and equals the fluid temperature coming between the shaped surfaces. The temperature fields in the surroundings of shaped heat exchange surfaces were visualised by holographic interferometry. For this purpose, a holographic variant of the Mach-Zehnder interferometer was created (according to the scheme in Fig. 1).

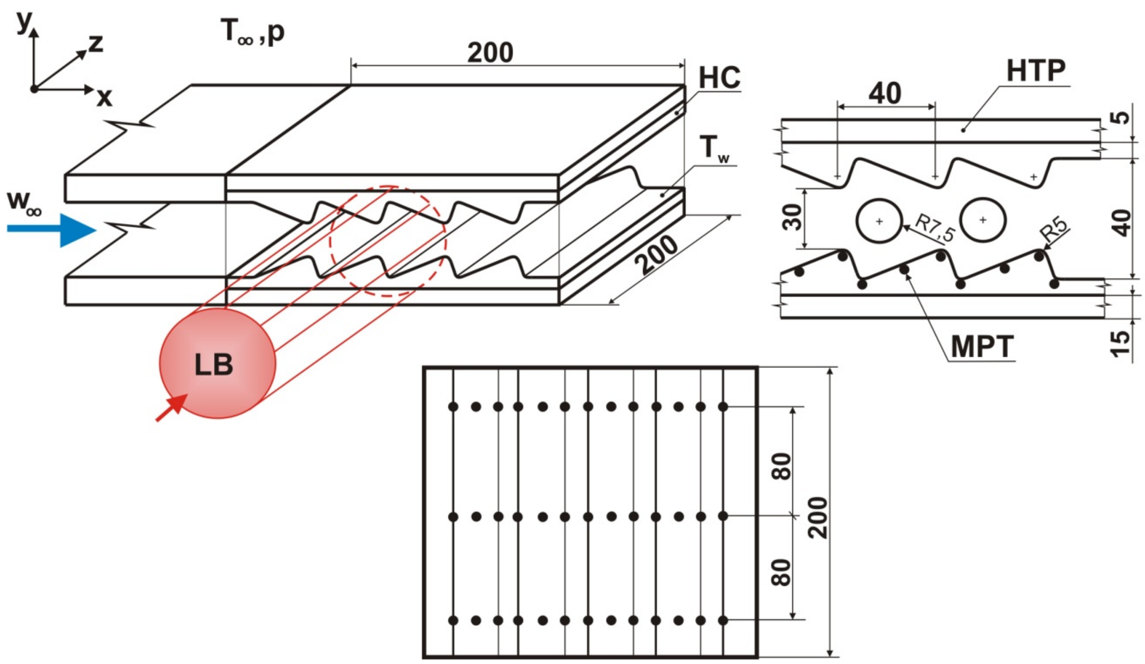


Fig. 3. Geometric arrangement of shaped heat exchange areas and measurement points for measuring the surface temperature (values in mm)

The obtained images of holographic interferograms were consequently qualitatively and quantitatively evaluated. Local values of heat transfer coefficients along the heated shaped surface without and with the regulating elements (ducts) were determined by a quantitative analysis. The visualisation and analysis were carried out on the heat exchange surfaces of a tear-shaped contour. A demonstration of a holographic interferogram image of a selected measuring part between the heated shaped surfaces with their vertical distance of 40 mm without the regulating ducts is shown in Figure 4a and with the regulating ducts in Figure 4b. The surface temperature of the tear-shaped contours was $T_w$ = 319.25 K and the surrounding temperature was $T_\infty$ = 295.15 K. The surface temperature of the tear-shaped contours was measured via resistance temperature sensors built into the shaped contours. Using a fan, the air with a velocity of $w_\infty$ = 0.2 m/s was blasted between the heated surfaces. A mean velocity of the air flow was measured by the ALMEMO thermoanemometer.

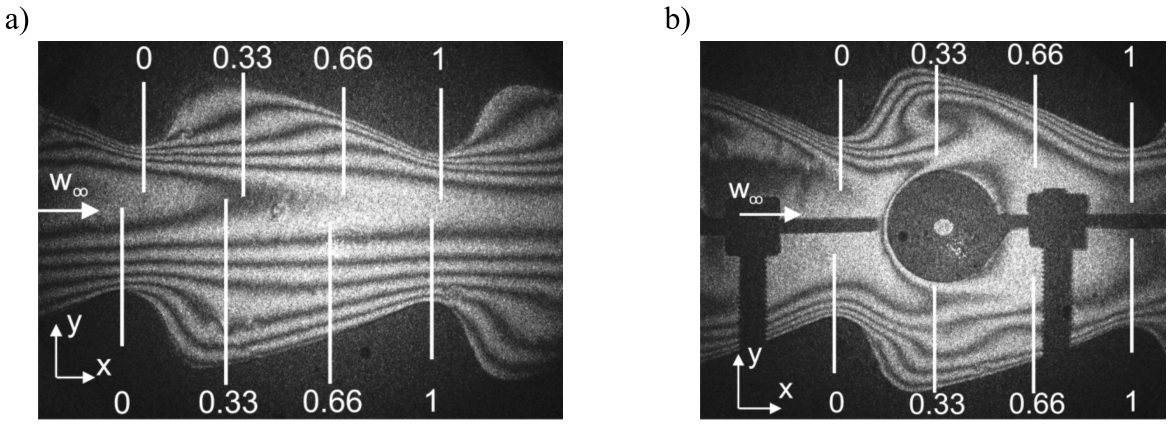


Fig. 4. Images of holographic interferograms at a vertical distance between the plates of 40 mm, the velocity of air flow 0.2 m/s in the labelled sections 0 to 1, a) without regulating ducts, b) with regulating ducts – diameter 15 mm

The obtained images form the holographic interferograms of temperature fields which were analysed with special software. After calibrating the dimensions and defining the marginal conditions respective temperatures were allocated to the particular interference stripes. Functional temperature dependence on the interference order was calculated according to Equation (8). As shown in Figure 5, it was possible to allocate coloured contours to the particular temperatures in the program.

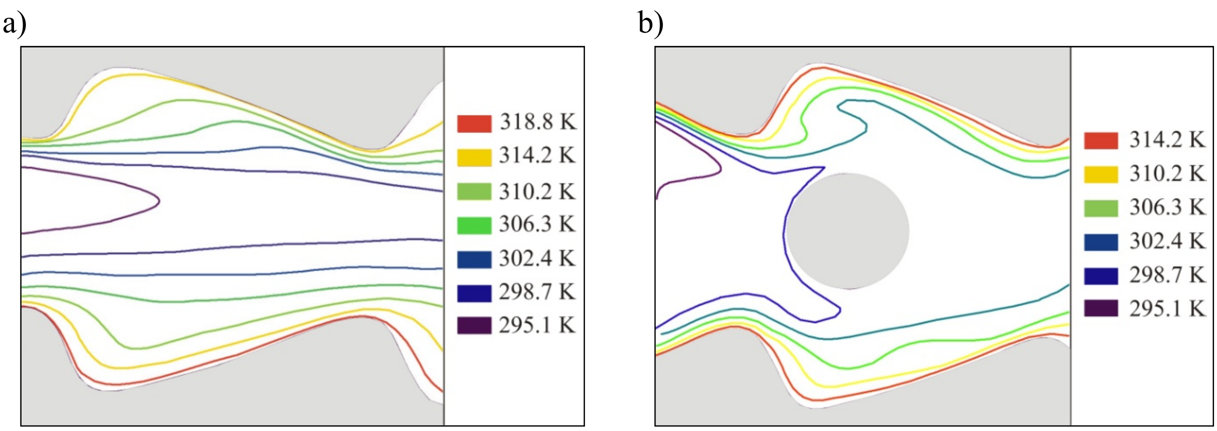


Fig. 5. Distribution of temperature fields between the heat exchange plates, a) without regulating ducts, b) with regulating ducts

As shown in Figure 4 or Figure 5, the regulating elements in the shape of a duct with a diameter of 15 mm affected the thermal boundary layer along the shaped surface and therefore the local heat transfer coefficients. The local values of heat transfer coefficients were determined in the indicated cuts (Fig. 4 a, b), in the dimensions expressed as a ratio x/s for 0; 0.33; 0.66 and 1. Spacing $s$ between the tops of the shaped heat exchange surfaces had a value of 40 mm. Yet in the qualitative analysis of the temperature field it is possible to observe a decrease in the thermal boundary layer thickness – thermal resistance decrease associated with an increase in local values of the heat transfer coefficient, $\alpha_x$. In the quantitative analysis of temperature fields the local values of heat transfer coefficients in the labelled sections in Figure 4a, b were calculated on the basis of Equation (11). The analysis was performed for the upper and lower heated contours, first, without the regulating ducts (Tab. 1) and consequently after their placement between the contours (Tab. 2). When applying a regulating duct the heat transfer coefficient in regard to the low velocity of air flow was increased.

Table 1. Local values of heat transfer coefficients on the lower and upper heated contours without regulating ducts

| $x/s$ | 0 | 0.33 | 0.66 | 1 |
|---|---|---|---|---|
| Lower contour $\alpha_x$, W/(m$^2$·K) | 5.09 | 1.87 | 3.01 | 5.18 |
| Upper contour $\alpha_x$, W/(m$^2$·K) | 13.72 | 2.09 | 6.02 | 12.37 |

Table 2. Local values of heat transfer coefficients on the lower and upper heated contours with regulating ducts

| $x/s$ | 0 | 0.33 | 0.66 | 1 |
|---|---|---|---|---|
| Lower contour $\alpha_x$, W/(m$^2$·K) | 10.79 | 3.05 | 5.95 | 10.62 |
| Upper contour $\alpha_x$, W/(m$^2$·K) | 13.19 | 9.27 | 13.19 | 16.02 |

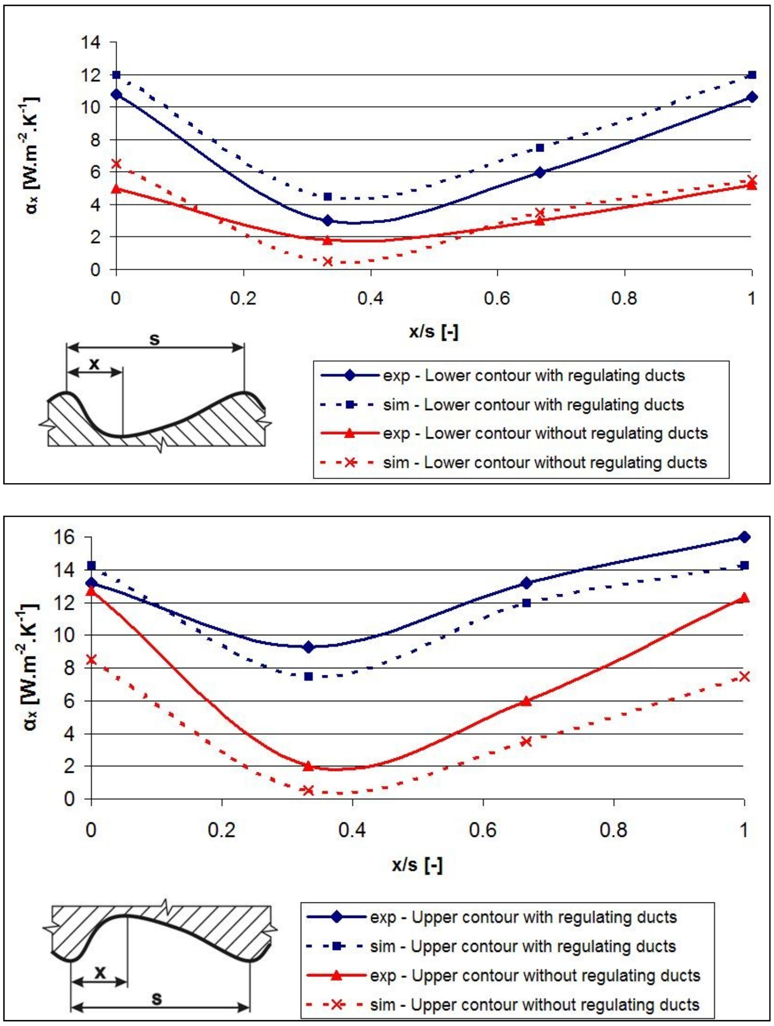


Fig. 6. A comparison of local heat transfer coefficients on the lower and upper heated contours with and without regulating ducts

From the experimental measurements (Fig. 4) it follows that the local values of heat transfer coefficients have different values along the shaped heat exchange area. As can be seen from the images of interferograms, the boundary layer thickness is changed along the shaped heat exchange area. In the places where the temperature boundary layer has a small thickness the heat exchange coefficient gains a higher value. The thickness of the temperature boundary layer can be influenced by the contour shape or by introducing a regulating element (Fig. 4b). The local values of heat transfer coefficients can be increased in this way.

Figure 6 shows a graphical comparison of the distribution of local values of heat transfer coefficients on the lower and upper heated contours.

## 5. CFD SIMULATIONS OF THE DISTRIBUTION OF LOCAL HEAT TRANSFER COEFFICIENTS ALONG THE HEAT EXCHANGE SHAPED SURFACES

Computational Fluid Dynamics (CFD) was used to compare the results obtained experimentally with a numerical solution. It enables an exact mathematical approximation of heat transfer processes and, simultaneously, it makes a design of shaped heat exchange areas of heat exchangers more effective. A commercial program FLUENT was used for CFD simulations.

Temperature field simulations between the heat exchange tear-shaped surfaces were carried out under the same conditions as the inteferometric measurements. The main input parameters for the CFD model were: geometric model dimensions, the same as the experimental apparatus dimensions, surface temperature, surrounding temperature and the velocity of air flow. A three-dimensional topological model was used for CFD simulations. A demonstration of a CFD simulation of the distribution of local heat transfer coefficients along the heated tear-shaped contour without regulating ducts is presented in Figure 7 and with them in Figure 8. The regions which were recorded and evaluated interferometrically are highlighted in the figures with a broken line.

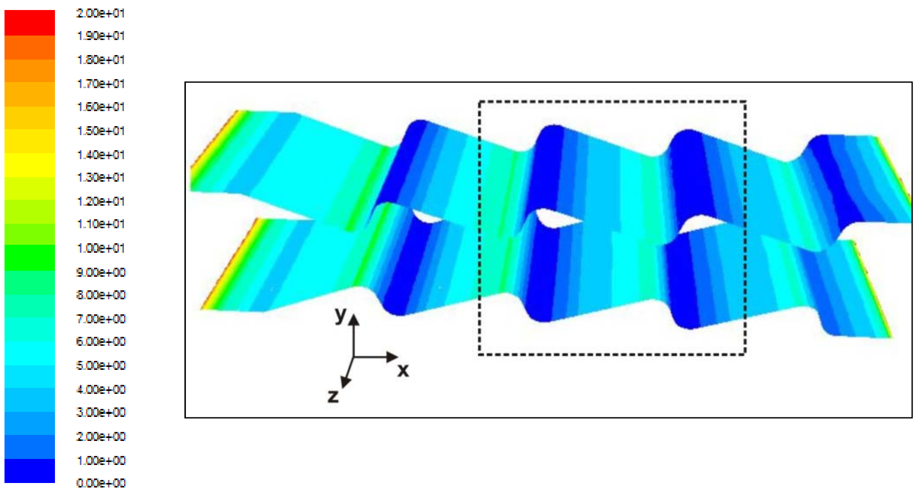


Fig. 7. A CFD simulation of the distribution of local heat transfer coefficients along the heat exchange tear-shaped contour without regulating ducts

As shown in Figure 7, the local heat transfer coefficients have the highest values in a restricted cross-section between the corrugated plates where the thickness of the thermal boundary layer is the smallest. These regions are coloured green. In the observed region these zones have the highest values of the heat transfer coefficients. In contrast, in the extended part where the thermal boundary layer has a fundamentally larger thickness the local values of heat transfer coefficients are smaller. These areas are coloured blue. Figure 8 shows that the local heat transfer coefficients have also the highest values in the restricted cross-section but also higher values in the extended part where a regulating duct is placed. By using the regulating ducts the local coefficients were considerably increased at the upper contour which might also have been caused by natural convection at the low velocities of air flow. In comparison with Figure 7 it is obvious that the local values of heat transfer coefficients were increased practically along the whole length of the lower and upper contours. Concrete numerical values of the local heat transfer coefficients are assigned in the figures.

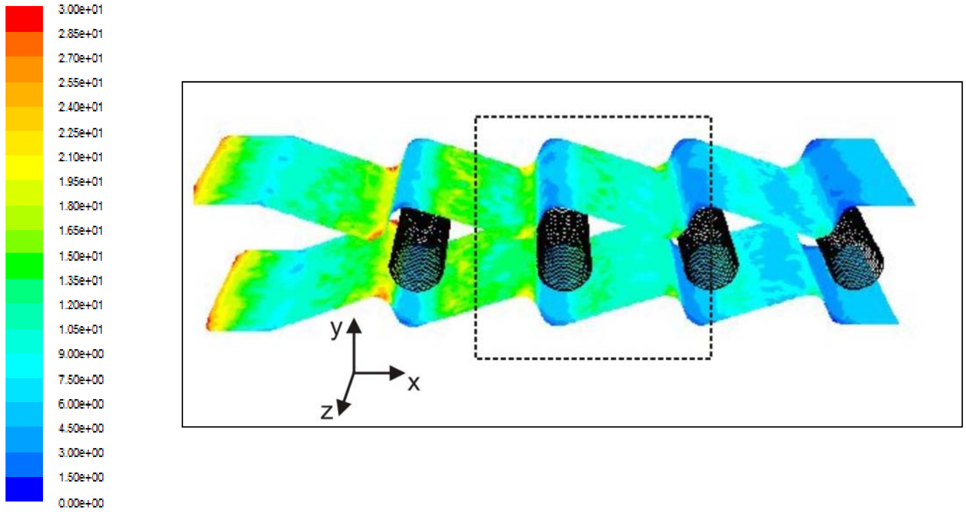


Fig. 8. A CFD simulation of the distribution of local heat transfer coefficients along the heat exchange tear-shaped contour using regulating ducts with a diameter of 15 mm

Comparing the findings of the local heat transfer coefficients obtained by the quantitative analysis from the images of holographic interferograms and the findings from the CFD simulations it is obvious that the values of the local heat transfer coefficients in the observed field are in good agreement.

## 6. CONCLUSIONS

The findings presented in the paper have shown that the visualisation method (holographic interferometry) applied in the experiments allows to study temperature distribution also at lower velocities of air flow in shaped complex contours. Forced convection is accompanied by natural convection at low velocities of the flowing air. The bigger the difference of temperatures in the system and the smaller the velocity of forced motion, the bigger the relative influence of the natural convection on the forced convection. A method of holographic interferometry enables sensitive recording of these complex processes also in multiple and spatially shaped contours.

The regulating ducts inserted into the flow direction steer the air flow into places with worse parameters of heat transfer. From the experimental findings and the CFD simulations it can be said that the inserted regulating ducts contributed to the increase in local heat transfer coefficients despite the low air flow velocity. It is suitable to use CFD simulations when studying physical phenomena acting in flow in heat exchange shaped areas, which can substantially reduce production costs and make expensive experiments unnecessary. Hence, the use of CFD simulations is significantly faster and more effective provided that the setup accuracy for CFD simulations was verified experimentally. The presented numerical findings of the local values of heat transfer coefficients are in good agreement with those obtained experimentally. The size of the investigated region by holographic interferometry was limited by the size of the objective lens visual field in the object measurement branch of the interferometer.

*The contribution was created within the KEGA project no. 027TUZVO-4/2011 funded by the Ministry of Education, Science, Research and Sport of the Slovak Republic.*

## SYMBOLS

| | |
|---|---|
| *A* | area, $m^2$ |
| *BS* | beam splitter |
| *C* | camera |
| *CCD* | Charge Coupled Device |
| *CFD* | Computational Fluid Dynamics |
| *CP* | corrugated plate |
| *F* | spatial filter |
| *HC* | heated contour |
| *He-Ne* | helium–neon |
| *HP* | holographic plate |
| *HTP* | heating plate |
| *K* | Gladstone-Dale constant, $m^3$/kg |
| *L* | length, m |
| *LA* | laser |
| *LB* | light beam |
| *LDA* | Laser Doppler Anemometry |
| *M* | mirror |
| *MO* | micro-objective lens |
| *MP* | measuring plane |
| *MPT* | measurement point |
| *MS* | measuring space |
| *N* | notebook |
| *n* | refractive index |
| *O* | objective lens |
| *p* | object beam |
| *p* | pressure, Pa |
| *q* | heat flow density, W/$m^2$ |
| *R* | radius, m |
| *r* | reference beam |
| *r* | gas constant, J/(kg.K) |
| *s* | spacing, m |
| *T* | temperature, K |
| *w* | velocity, m/s |
| *x* | location along *x* coordinate, m |
| *x, y, z* | coordinate system axes |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | heat transfer coefficient, W/($m^2$.K) |
| $\beta$ | angle, ° |
| $\delta$ | thickness of thermal boundary layer, m |
| $\Delta o$ | optical path change, m |
| $\Delta s$ | interference order change |
| $\phi$ | heat flow, W |
| $\lambda$ | thermal conductivity coefficient, W/(m.K) |
| $\lambda$ | wavelength of light, m |

| | |
|---|---|
| $\rho$ | density, kg/m$^3$ |

*Subscripts*

| | |
|---|---|
| *ai* | air |
| *w* | wall, surface |
| *x* | local value |
| ∞ | ambient surroundings |

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*Received 16 April 2012*
*Received in revised form 15 December 2012*
*Accepted 19 December 2012*