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Liquid Crystal Technique Application for Heat Transfer Investigation in a Fin-Tube Heat Exchanger Element

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***Abstract*:** The use of thermochromic liquid crystal technique (LCT) and true-colour image processing system in heat transfer modelling is described. Experimental procedure, led on rig at Technical University of Gdansk, cover full-field flow patterns in heat exchanger element (flat plate with fine-tubes in-line, staggered and with vortex generators) describing local heat transfer coefficient and Nusselt number on the surfaces. Also the dependence of average heat transfer and pressure drop on Reynolds number and geometrical parameters is investigated.

***Keywords*:** thermochromic liquid crystals, heat transfer, wind tunnel, vortex generator.

***Nomenclature*:**
H - height of the channel [m]
k_a - conductivity of the air [W/m K]
k_t - mean conductivity of the liquid crystal package and plate [W/m K]
L - the length of the channel in the main flow direction [m]
ΔP - pressure drop [Pa]
r_i - Hue ratio coefficient (ratio of number of pixels for the hue range considered) [-]
T_a - temperature of air [K]
T_b - temperature of plate on waterside [K]
T_l - temperature of surface (liquid crystal yellow-green isotherm temperature) [K]
U - inlet mean velocity [m/s]
δ_t - thickness of the liquid crystal package and plate [m]
ρ - air density [kg/m^3]
ν - viscosity of air [m^2/s]

1. Introduction

For the last decade liquid crystals (LCs) have been successfully used in many experimental works. Aerodynamics, Fluid Mechanics, Heat Exchange or Aeronautics are the most important fields where LCs were used. The experimental technique, used by numerous experimentalists in heat transfer problems is interesting and promising (Stasiek and Collins, 1996; Baughn and Yan, 1991; Jones et al., 1992; Moffat, 1991). Liquid crystals are highly anisotropic fluids that exist between the boundaries of the solid phase, and the conventional, isotropic liquid phase. Since the colour change is reversible and repeatable, they can be calibrated accurately with proper care and used in this way as temperature indicators. They can be painted on a surface or suspended in a fluid and used to indicate visibly the temperature distribution. Nowadays, colour image processing has become an integral part of many scientific and industrial applications. A great majority of applications that use colour image processing do so because colour is the most important and obvious feature of the images they are examining. These new tools (liquid crystals, computers and image processing) have come together during the past few years to produce a powerful new examination technique: true-colour digital processing of liquid crystal images to yield full-field temperature, velocity and heat transfer coefficient distribution (Hollingsworth et al., 1989; Stasiek, 1998; Stasiek and Collins, 1996). Now, new and more incisive experiments are being settled in conventional situations, while those which have been previously intractable can also be studied. In this paper a novel approach is suggested to calculate heat transfer coefficient. The method is based on counting the number of pixels and their corresponding values of measured quantity. This method has been illustrated on examples of complex geometrical configurations.

2. Experimental Apparatus

The experimental apparatus used in this study is the same as that presented before by Wierzbowski et al. (1998). A brief description of the test section is presented here for clarification. The experimental study is carried out using an open low-speed wind tunnel consisting of entrance section with fan and heater, large settling chamber and then mapping and working sections. Air is drawn through the tunnel using a fan to provide Reynolds numbers between 500 and 10 000 and the heater, which can adjust air temperature T_f between 25 and 60°C.

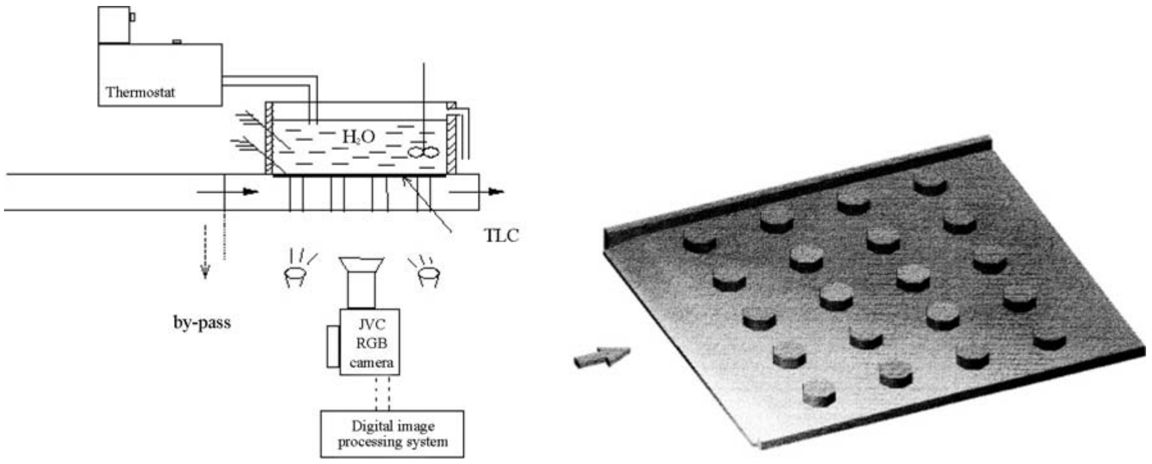

Fig. 1. Experimental set-up and fin-tube heat exchanger model for in-line arrangement.

The major construction material of the wind tunnel is Perspex. Local and mean velocity are measured using conventional Pitot tubes and DISA hot-wire velocity probe. Test section is of 7 mm height, 320 mm width and 350 mm length. Pipes are of 30 mm diameter, while winglets are 14 mm long and distanced 2 mm from the tube (Fig. 2). The alternative effects of constant wall temperature and constant heat flux boundary conditions are obtained using a water bath. Photographs of liquid crystal patterns are taken using a colour video camera and a true-colour image processing technique. It is possible, thanks to a special by-pass installed, to measure using both steady state and transient technique (Fig. 1). Local heat transfer measurements are carried out for Reynolds number based on the centreline inlet velocity along the main flow direction. Local heat transfer coefficient and Nusselt number maps, derived from local wall-temperature distributions as indicated by LCs for different Reynolds number are reported below. False colour isotherm representation of local Nusselt number was made automatically by GLAB software of Data Translation Inc. (1991). The experiment is reported for fin-tube heat exchanger elements, both in-line and staggered. Air flows around the tubes and heat transfer between the fluid and the plate are determined by the flow structure.

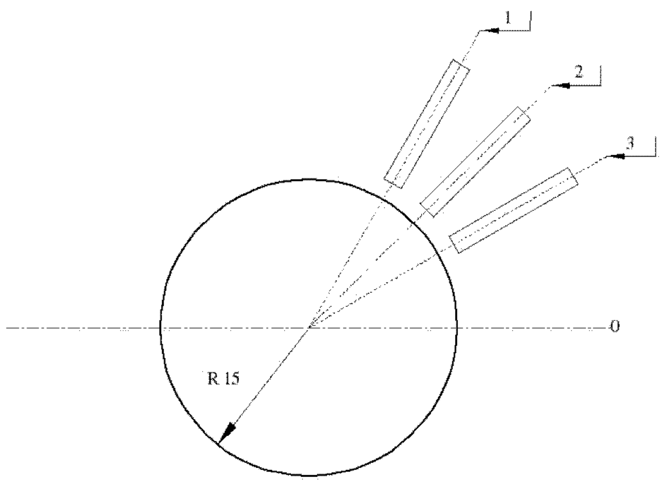

Fig. 2. Position of the winglet behind the tube (1- 30 deg, 2- 45 deg, 3- 60 deg).

3. Performance Parameters

3.1 Heat Transfer

The heat transfer coefficient is a defined quantity, calculated from the surface heat flux and the difference between the surface temperature and some agreed reference temperature. This is usually the bulk temperature, the mixed mean temperature or the adiabatic surface temperature. In the experiment described here, liquid crystals were used to determine the distribution of surface temperature and heat flux. This allows evaluation of the local heat transfer coefficient and Nusselt number. The temperature recorded from the liquid crystal sheet was held at yellow-green for image processing.

The local convective heat transfer coefficient h_l is derived from the fact that the conductive heat flux q_k in either working section is equal to the convective heat flux from air to the surface in the steady state (also taking into account that if the working section surface is thin and of high conductivity material, than it will respond as element with no lateral conduction (Moffat, 1991)):

$$h_l = \frac{k_t}{d_t} \frac{(T_l - T_b)}{(T_a - T_l)} \tag{1}$$

The experimental results are presented in terms of a local Nusselt number:

$$Nu_i = h_l H/k_a \tag{2}$$

The Nusselt number value requires the test plate thermal conductance to be evaluated. It can be measured by imposing a one-dimensional conductive heat flux across a sample having the composition and thickness as the test plate and measuring the extent of the heat flux and the temperature drop between the opposite sides. The measurement was performed by use of thermal conditions occurring in the liquid crystal experiment. Thermal conductivity of the test plate can be deduced from thermal conductance, which turned out to be $k_t = 0.202$ W/m K. With the temperature difference between the air and liquid crystal isotherm fixed, different heat transfer coefficient (Nusselt number) contours are determined by varying the heat flux values. The contours of constant heat transfer coefficient are not directly equivalent to the isotherms, as measured from the images. They are determined after taking into account thermal conduction in the plate, radiation from the surface and other corrections, which is typically about 5% of the net flux (Hollingsworth et al., 1989; Stasiek, 1998). The liquid crystal colour temperature T_l is 35.5°C, some 9.5°C below the air temperature (T_a = 45°C) for these experiments. Ten to sixteen isotherms (each corresponding to a different heat flux) are photographed by RGB camera to record the local contours under a specified Reynolds number. The location of each isotherm was digitised involving colour scale representation of the several video images of the heat transfer coefficient distribution into a single image using the Global Lab software of Data Translation Inc. (1991) as described in Stasiek and Collins (1996) and Wierzbowski et al. (1998).

Average Nusselt numbers can be estimated as weighted mean values of the local Nusselt numbers obtained from the relationship:

$$Nu_{av} = \frac{\sum_{i=1}^{n} Nu_i r_i}{\sum_{i=1}^{n} r_i} \tag{3}$$

By using Eqs.(1)-(3) and the image combination technique capabilities of Global Lab, colour images like that in figures below were obtained.

3.2 Pressure Drop

The second most relevant performance parameter of the heat exchange matrix is the pressure drop per unit length. The pressure drop can be made dimensionless by defining the equivalent friction factors coefficient:

$$f = \frac{2 \Delta P H}{\rho L U^2} \tag{4}$$

The experimental results are summarised in Figs. 3 and 4.

Reynolds number values were calculated as:

$$Re = \frac{U \cdot H}{\nu} \tag{5}$$

Both friction factor and Reynolds number are related to mean velocity U and height of the tunnel H, which can correlate $f = f(Re)$.

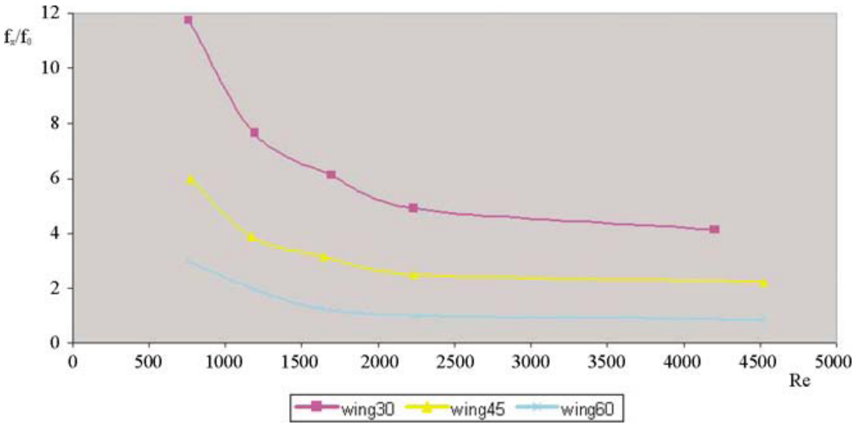

Fig. 3. Friction factor distribution for in-line arrangement of working section.

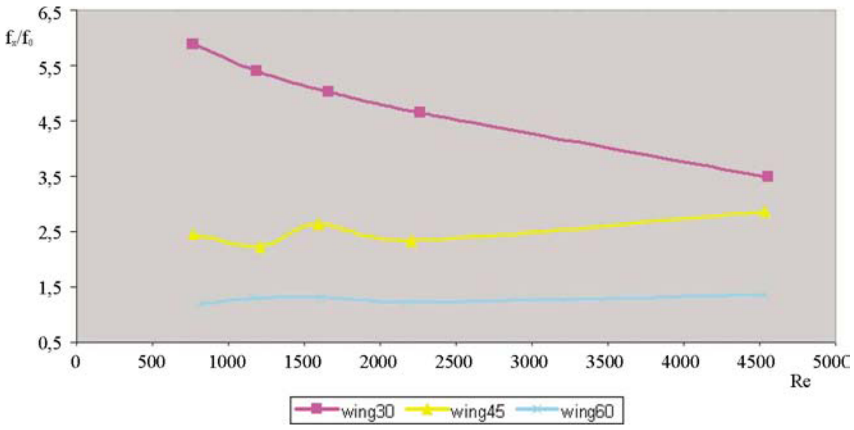

Fig. 4. Friction factor distribution for staggered arrangement of working section.

4. Experimental Results

4.1 Channel Averaged Pressure Drop

Figures of friction factor versus Reynolds number show the comparison of the different layout of the test section (in-line or staggered). It is easy to find out that in both applications insert of wings angled 60 degrees causes less pressure drop than the other positioning. It is clear to find hydraulic jump at the transitional region of Reynolds number 1 000 - 2 500 both for 30 and 45 degrees positioned winglets.

4.2 Local Nusselt Number Maps

Photographs are taken using a video camera and a true-colour image processing technique. Usually several isotherms (each corresponding to a different heat flux) are taken by camera to record the local Nusselt contours under a unique Reynolds number. The locations of each isotherm and colour (adjusted to each Nusselt number) are digitised following a projection of the false colour image on a digitising image respectively. Figures 5-7 show colour-scale representation of Nusselt number distribution around in-line and staggered configuration of cylinders in experimental section. Averaged Nusselt number distribution graphs illustrated (Figs. 8 and 9) show that not always implementation of vortex generators results in heat transfer increase. Most important is that pressure drop and Nusselt number characteristics have merely the same character in laminar and transition flow region. The maximum error of the air temperature is 0.1°C and 0.025°C for the water bath. The uncertainty of thermal conductivity measurements for plate - liquid crystal package is about 0.005 W/m K. The most important factor seems to be the temperature difference between the water bath and liquid crystal layer temperature. When the difference is small the error significantly increases.

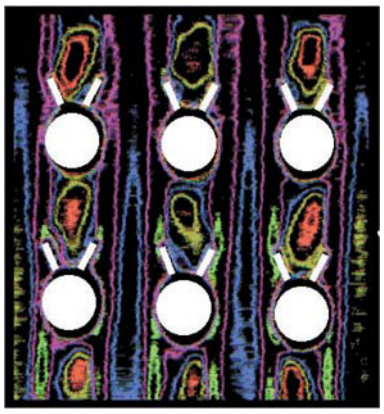

Fig. 5. In-line arrangement for *Re* = 2 250 (Nusselt number: red - 5.01; brown - 7.46; blue - 11.33; violet - 17.72; green - 27.76).

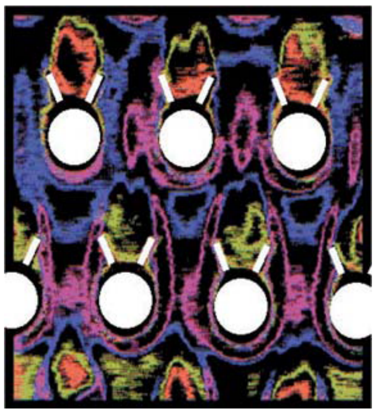

Fig. 6. Colour-scale representation of Nusselt number for staggered cylinders. *Re* = 1 600 (Nusselt number: red - 5.27; green - 7.99; blue - 15.38; violet - 19.17).

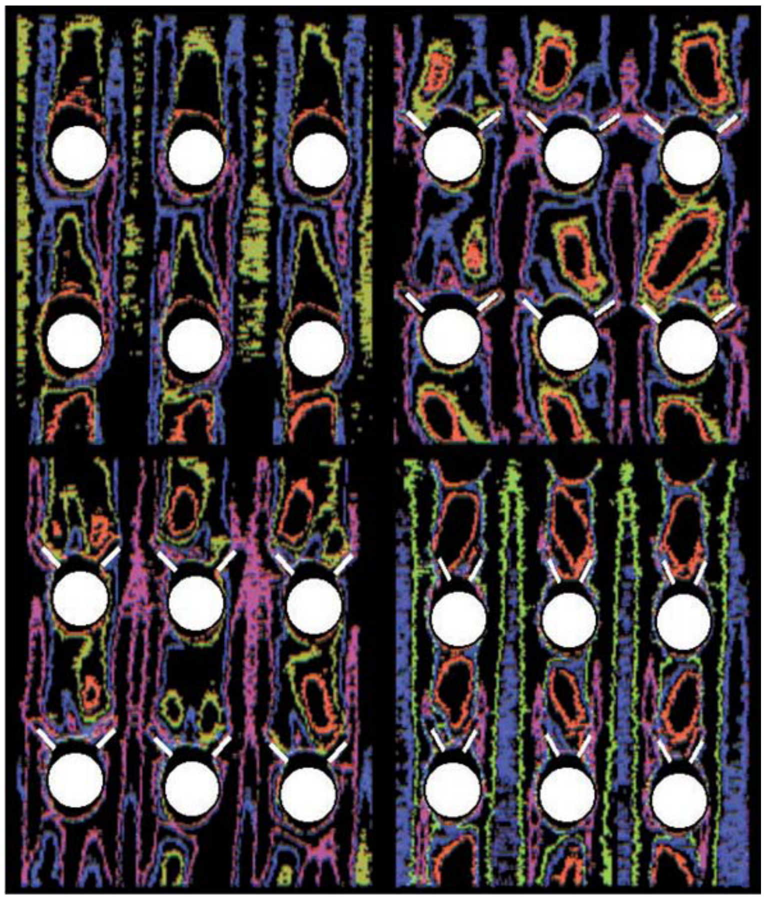

Fig. 7. In-line working section for different wing's experimental arrangement. *Re* = 1 200 (clockwise: no wing, wing 30 deg, wing 60 deg and wing 45 deg).

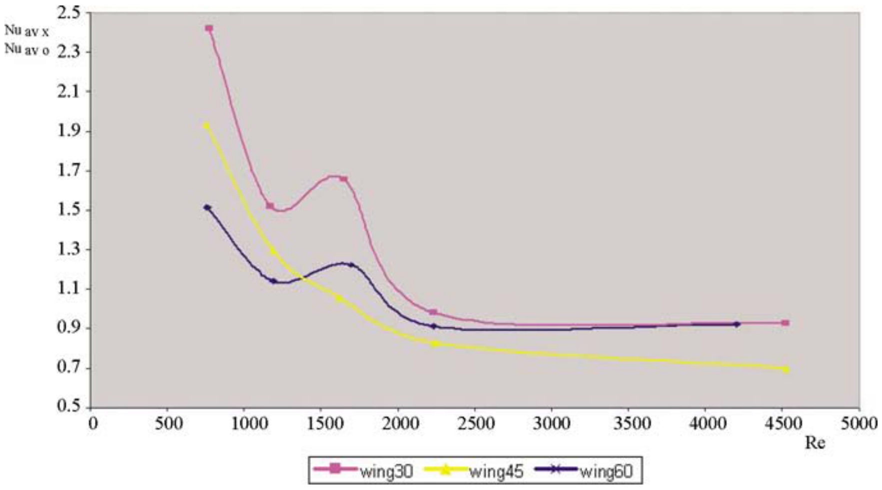

Fig. 8. Averaged Nusselt number distribution for in-line arrangement of working section.

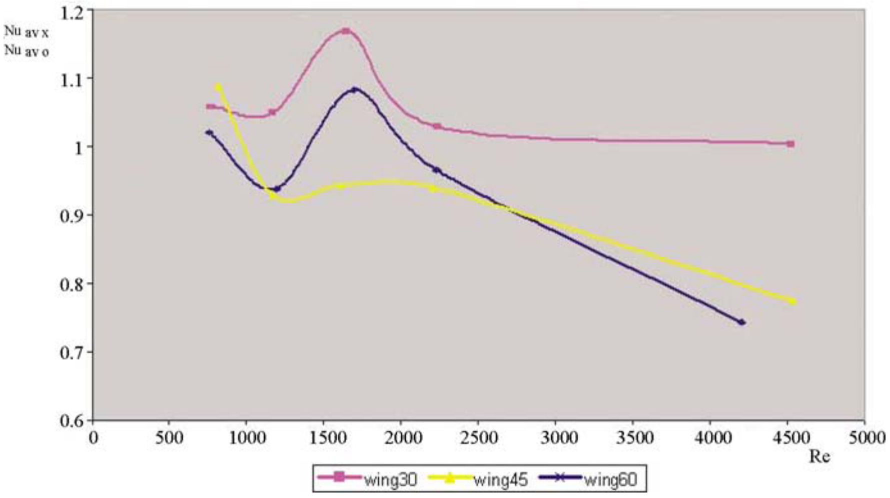

Fig. 9. Averaged Nusselt number distribution for staggered arrangement of working section.

5. Conclusions

Liquid Crystal Technique (LCT) is fairly new and powerful. With no doubts we can agree that new powerful technique has been established for obtaining local heat transfer conditions in complicated geometries, which can be useful for developing of different areas of heat transfer research. This technique is especially good for investigation of complex geometry heat transfer problems for example presented and discussed in this paper.

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