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The Use of Thermochromic Liquid Crystals to Investigate Heat Transfer Enhancement in a Channel with a Protrusion

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Abstract

Thermochromic liquid crystals (TLCs) were used to investigate the effectiveness of a single protrusion (a hemisphere of 10mm diameter) for enhancement of heat transfer in a 10mm x 40mm cross-section channel filled with warm water flowing at Reynolds numbers of approximately 570 and 1000. The channel was separated from an adjacent channel of colder water by an aluminium plate. Two methods were used in order to gain the maximum possible information for comparison to numerical results: a crystal-coated sheet applied to the surface of the channel featuring the protrusion, and suspended crystals illuminated by a sheet of light to create a “slice” down the centreline of the channel. The on-surface technique yielded useful data which compared extremely well to CFD, and the suspended crystals provided an additional level of insight, though their use in such a small channel with only a simple light sheet and optics produced sub-optimal results. Overall, the techniques applied show promise, but are most effective when combined with additional information gained from other experimental techniques and numerical modelling to provide the greatest level of knowledge of the flowfield.

Introduction

Many ideas have been proposed and studied for improving the effectiveness of heat transfer in heat exchanger channels. These include passive surface modifications such as pin fins, rib turbulators and protrusions (Wei et al., 2007). It is worth noting that although an enhancement in heat transfer is achieved by these obstacles, an associated pressure drop penalty is incurred.

Numerically, Alshroof *et al* [1] managed to achieve 7% enhancement in the total heat transfer rate in a shallow rectangular channel using single small protrusion (height/diameter, h/D=0.22). The pressure penalty increased only 1% compared to a smooth channel, and thus the gain in performance was effective. Recently, new technology has been developed and used to visualise the surface temperature of heat exchangers using infrared thermography. Ligrani *et al* [2] and Mahmood *et al* [3] used this technique to study the heat transfer in a channel with array of dimples and/or protrusions introduced in both bottom and top surface of a rectangular channel.

Chyu *et al* [4] investigated the local heat transfer in the vicinity of arrays of spherical and tear-drop dimples shapes, using a thermochromic liquid crystal (TLC) coating on the dimpled surface. Hwang *et al* [5] used the same (TLC) technique to study the enhancement of heat transfer and the pressure drop for a channel with array of dimples and/or protrusions. For the protruded surface, horseshoe vortices were generated thereby enhancing heat transfer on the front surface of the protrusion. On the other hand, a low heat transfer region existed on the back surface of the protrusion due to the wake downstream of the obstacle. The highest heat transfer flux occurred on the protruded surface, but, as may have been expected, this was also the area of maximum sheer stress.

In the current study, the liquid crystals served a dual function whether applied as a sheet to the channel wall which featured the protrusion (after the method described by Smitts and Lim [6], or suspended in the fluid in similar fashion to less complex flows examined in considerable detail by Ciofalo et. al [7]. Here the crystals provided a useful level of flow visualisation, and they also afforded reasonable resolution of the quantitative temperature field on lit planes without disturbing the flow. The suitability or otherwise of novel application of suspended crystals to a problem featuring significant geometric disruption to the flow is discussed.

Experimental apparatus

Two water cycles were built as shown in Figure 1 to separate the hot and cold water flows. A simple parallel flow heat exchanger consisting of shallow rectangular channels was built, as per the cross section shown in Figure 2. The “top” channel, in which hot water flows at low Reynolds numbers, was separated by a 7.5 *mm* thick aluminium plate from the “bottom” channel encasing the rapidly flowing cold water. A hemispherical protrusion of 10mm diameter was placed on the centerline of the aluminium plate 230mm from the inlet. The test rig was designed in such way as to minimize any disturbance of the flow upstream of the protrusion. The cross-sectional dimensions were 40x10 *mm* for the top hot water channel and 40x20 *mm* for the bottom cold water channel.

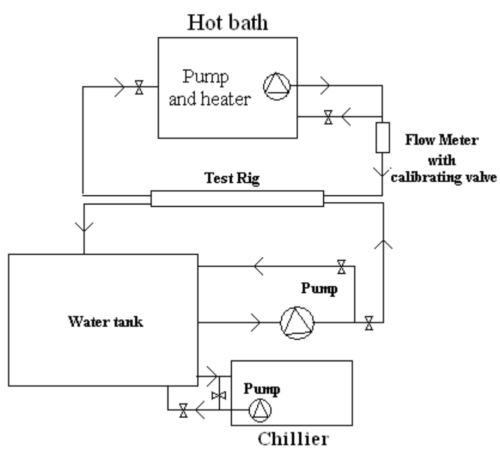

Figure 1. Schematic view of heat exchanger.

Since the pumps are connected to the channel of the heat exchanger through circular cross-section pipe lines, a diffuser was installed between the inlet pipes and the rectangular channels.

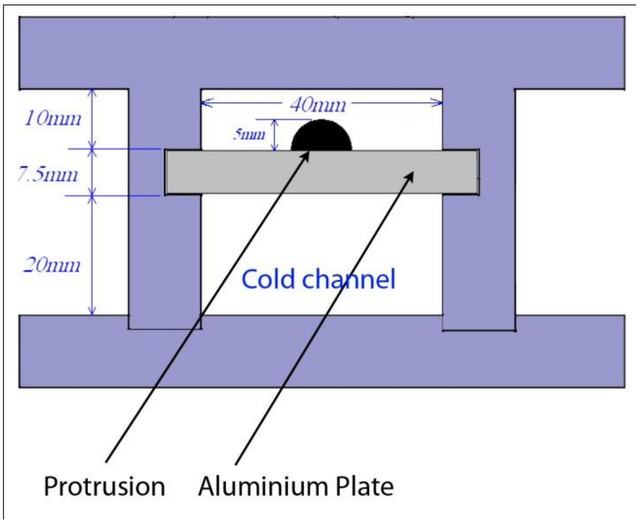

Figure 2. A cross-section through the channels of the heat exchanger, showing the location of the protrusion in the warm water channel.

Thermochromic liquid crystals (TLC)

Thermochromic liquid crystals are highly anisotropic fluids which reflect definite colours at specific temperatures and viewing angles. They are commonly used for the quantitative visualisation and quantitative measurement of temperature fields in fluids. The colour change for the crystals ranges from clear, through red as temperature increases, to yellow, green, blue and violet until a clear state is reached again at a high temperature. The colour play interval must be problem-specific, and the range selected to provide the most detailed resolution possible for the image frame. By calibrating the red, green and blue (RGB) for the whole colour range within the spectrum from red to blue, the stored images are then quantified to produce temperature measurements and temperature distribution maps.

Three methods can be used for surface temperature measurements. The first option is to apply a coating containing TLC to the surface. This needs to be done very carefully as rough surfaces could change the flow structure over the top, which could lead to changes in the temperature distribution over that surface. The second option is to affix TLC sheets, which contain a thin film of the liquid crystal sandwiched between transparent polyester sheets, to flat surfaces such that the sheets are flush with their surroundings. The sheets have a similar surface finish to a smooth bare surface, and thus this technique useful because the flow structure is not changed.

Finally, the liquid crystals can be suspended in the water to measure the thermal field in the channel. The density of the suspended liquid crystal is equivalent to that of water [8].

For the present experiments, the latter two methods were implemented. Examples of the images obtained are shown in Figure 3 (enhanced for clarity), prior to extensive post-processing. Standard halogen lights were used to evenly flood the channel for the on-surface method, while fibre-optic light passed through a narrow slit was used to create the light sheet for the suspended-crystal method. Figure 3 indicates that, due to the scattering of light from the protrusion surface as a result of the curvature, a "halo" is present which somewhat distorts the information in the colour distribution close to the surface of the protrusion. Additionally, the light sheet was approximately 1-2mm in the channel. While more narrow than is often the case for TLC experiments [9], this represents a significant portion of the protrusion diameter and channel width, and thus for small scale experiments the technique has unfortunate limitations using conventional lighting – only with a much more expensive setup could one achieve a true small-width light sheet, though the reduction in light intensity may require more sensitive optics.

The liquid crystal slurry was used in water at a concentration of approximately 300ppm and was chosen to have an operating range from 30 to 35^{o}C to best target experimental conditions.

System calibration

The thermocouples were calibrated in position at the inlets and outlets of the both channels in the heat exchanger. Since the temperature used in water calibration was that of the hot bath, the heat loss between water bath and the test section had to be minimized. This was achieved by insulating all pipes as well as the test rig. The system was operated for about an hour to reach its steady state, all four thermocouples reading were taken by the data logger and the water bath temperature was recorded.

The flow rate at the hot channel was set to get a Reynolds number, based on the hydraulic diameter (Re_{hd}), equal to 568 at constant temperature of 37.5°C for nominally steady-state flow, and at 1025 to create unsteady behaviour. The cold channel was maintained at a constant temperature of 27°C.

In order to obtain information beyond simple flow visualisation (which is valuable in itself) the liquid crystals were calibrated using a simple procedure of gaining images of uniform hue for known water temperatures through the active range, at intervals of 0.5^{o}C.

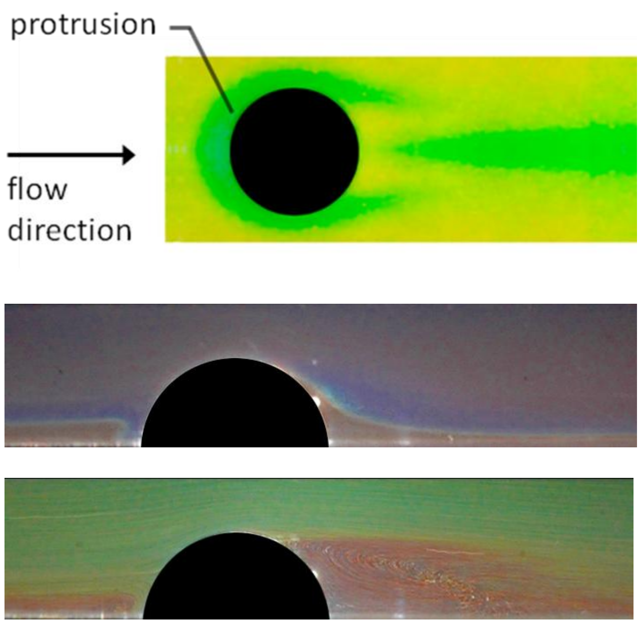

Figure 3. Typical image obtained from the experiment: (top) the sheet during a calibration test, and (below) in-plane, with colour enhancement, for Re of approx 550 and (bottom) 1025.

For instance, in the case of the TLC sheet located on the top surface of the aluminium plate, a high speed, linear-response RGB colour camera was placed perpendicular to the test section. Following Hay and Hollingsworth [10], the light from the halogen light source was inclined at 65° to the test section.

A MATLAB routine was used to covert RBG map images from the camera to HSV colour space components. The hue was smoothed by applying filters within MATLAB. From the calibration curve, the RGB image was converted to a temperature map.

Results and discussion

The post processed image shown at top in fig. 3 represents the centre (longitudinal) plane temperature for the higher Reynolds number case. The temperature contour shows higher temperature regions at stagnation point and then a significant level of mixing with colder fluid from the wall region downstream of the protrusion. This is a result of the hot fluid which been forced toward the bottom cold surface (the aluminium sheet), which disturbs the thermal boundary layer both upstream and the downstream of the protrusion. These high temperature regions are considered to be high heat transfer regions, and the downstream region extends for a long distance downstream, to about 10 protrusion diameters. Therefore, the single hemisphere in a shallow rectangular channel generates secondary flow which can be considered a good mixing mechanism, even at a low Reynolds number of 570.

One of the main reasons for undertaking the TLC experiments was to validate an extensive CFD programme consisting of simulations at a variety of Reynolds numbers, temperatures, etc. Some numerical results are presented here to show how the experimental results informed the CFD and vice-versa. The simulations were undertaken on fully-structured meshes of around 3.8 million cells using a commercial Reynolds-averaged Navier Stokes solver. For the sake of brevity, further details are not presented here but a full description of the numerical method, including extensive verification and validation, can be found in literature [1].

The post-processed TLC image shown in fig. 4 indicates that the mixing in the immediate wake and further downstream is significant and that the increment to heat transfer efficiency caused the protrusion is large. The agreement with CFD is reasonable given that the flowfield is transient and that an accurate match between a point in time in the simulation and the moment of the TLC photograph has to be judged based on the shedding frequency.

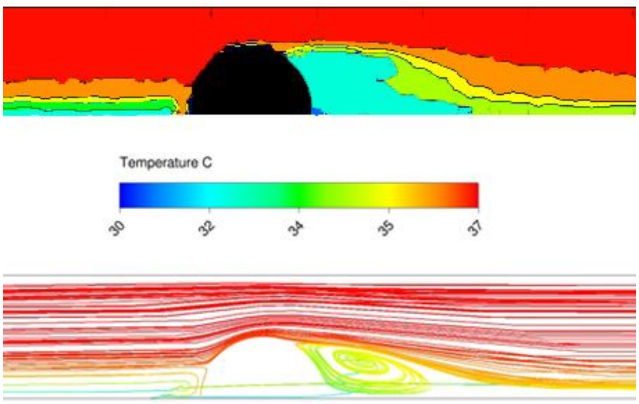

Figure 4. (top) Post-processed TLC and (bottom) CFD pathlines coloured by temperature indicate the extent of mixing, Re = 1025.

Without the additional information gleaned from the CFD, however, it would not be possible to understand the full three-dimensional flowfield without more extensive data from, for instance, particle image velocimetry on multiple planes at a very high resolution in both space and time.

As purely a visualisation tool, the in plane TLC highlights transient behaviour in the mid-plane of the channel at higher Reynolds number of 1025, based on the hydraulic diameter, as shown in Figure 5 from a sequence spanning approximately 2 seconds of flow time. Regular shedding in the wake of the protrusion is clear even in the raw images from the experiment, and was instructive in pointing to a need for transient simulation in CFD in order to capture this behaviour: a timestep of $7x10^{-5}$ was utilised to capture the full resolution of the flow evolution numerically.

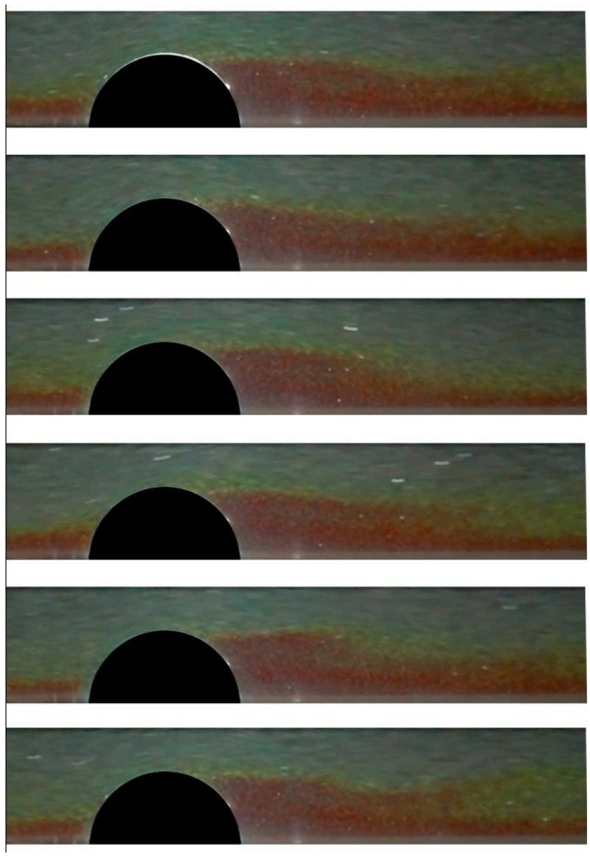

Figure 5. A 2s sequence of raw images from the in-plane TLC experiment showing unsteady behaviour in the wake of the protrusion.

The numerical results provided an additional, complementary insight into the flow features observed in the images, indicating a complex series of flow paths and vortices. Discussion of the complex vortex structures found in the flowfield can be obtained in literature [1].

The colder fluid which moves around the protrusion starts to change direction toward the bottom surface upstream of the protrusion as a result of the horseshoe vortex rotational motion, which starts upstream of the protrusion, therefore increases the heat transfer rate on that region and before it enters the wake region, where its located at either sides of the outer region of the wake. This fluid then enters the wake region from behind, then moves recirculates and washes out the back surface of the protrusion.

A further demonstration of the effectiveness of the validation of the CFD from the on-surface TLC measurements is shown in Figure 6, where the numerical data and experimental results from the on-surface TLC measurements match extremely well, with only mild differences occurring in the region close to the stagnation point of the protrusion. This image also shows the way in which the far wake from the protrusion continues to enhance heat transfer many diameters downstream of the disturbance itself.

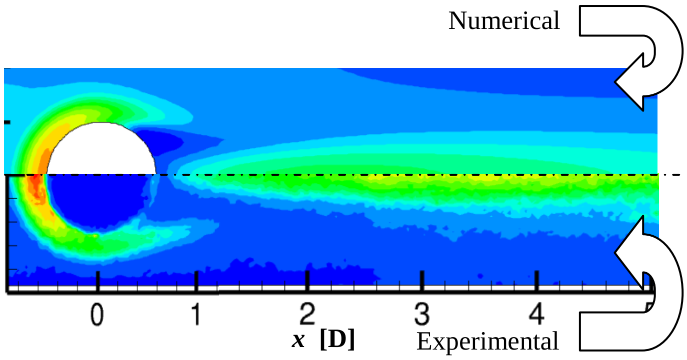

Figure 6. Temperature contours obtained using both numerical and experimental data for Re = 568.

Conclusions

One can see that a combination of on-surface measurements, in-plane measurements, and both steady-state and transient CFD produces a wealth of information about the flowfield using relatively simple, low-cost methods. The in-plane lighting of suspended crystals is problematic as a degree of light-scattering and chromatic aberration is present as the nominally planar light sheet reflects from the curved protrusion. Only switching to a more complex lighting and image-capture arrangement would abate this. However the transient nature of the flowfield at a Reynolds number of 1025 is can be clearly observed and a shedding frequency deduced.

At a lower Reynolds number of 568, an excellent match was found between numerical and experimental data using the on-surface TLC measurements. With the CFD validated and additional insight into the transient nature of the flowfield gained, the potential for future reliable numerical analysis is greatly improved.

Future work will expand the experimental programme to include a more comprehensive and parametric study, but this initial work bodes reasonably well for the prospects of gaining a good database of heat transfer results for a variety of conditions.

Acknowledgments

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