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A method to visualise near wall fluid flow patterns using locally resolved heat transfer experiments

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ABSTRACT

The present study demonstrates an alternative approach for describing fluid flow characteristics very close to the wall, using locally resolved convective heat transfer experiments. Heat transfer coefficients on the base surface and around a surface mounted vortex generator of delta-wing shape design, are evaluated with the transient liquid crystal measurement technique and over a range of freestream velocities. Therefore, the local values of exponent m in the equation $Nu_x \sim Re_x^m$, which is directly linked to the structure of the boundary layer, can be determined over the complete heat transfer area. The local distributions of exponent m are then directly compared to the footprint of the flow obtained with typical oil and dye surface flow visualisation. The results indicate that a more appropriate interpretation of the flow structures very close to the wall is possible by analysing the spatial variation of exponent m, which approximates better the flow pattern compared to the heat transfer coefficients. As a result, fluid flow topologies can be directly evaluated from the heat transfer experiments since the distributions of oil-flow visualisation and exponent m are qualitatively similar.

1. Introduction

Due to the difficulty in predicting accurately convection transport processes using numerical methods, experimental work is preferably carried out under controlled laboratory conditions correlating the heat transfer level in dimensionless parameters, usually described by the following semi-empirical expression [1]:

$$\frac{hx}{k} = Nu_x \approx C Re_x^m Pr^n \tag{1}$$

where coefficient C and exponents m and n vary with the nature of the fluid and the surface geometry. For laboratory test cases where air is the working fluid, exponent n equals 0.33 and 0.4 for heating and cooling conditions, respectively. It is also well established by analytical and empirical models, that typical values of exponent m vary between 0.5 and 0.8 for laminar and turbulent boundary layer flow, while for turbulent separated flows, exponent m is close to 0.66 representing the two-third power law ($Nu \sim Re^{2/3}$) which was found experimentally in the early 1960s [2] and confirmed later by Gorin and Sikovskii [3] and Gorin [4]. Note that similar trends can be also expressed for the regression coefficient C, however, with lower and higher values appearing for turbulent and laminar flow structures, respectively. Therefore, the level of local heat transfer coefficients at a given flow rate is highly dependent on the local state of the flow (i.e. local velocity, turbulence intensity, wall shear stress) and exponent m is somehow related to the structure of the boundary layer.

Subsequently, more turbulent flow does not strictly imply higher local heat transfer coefficients since the lower values of exponent m experienced in case of a laminar boundary layer can be easily compensated by the increased values of coefficient C, which results in increased Nusselt numbers at a given freestream velocity. A typical example can be found on impingement flows where the heat transfer is maximised on the stagnation point regions which are characterised by the development of a laminar boundary layer [5]. This means that in the absence of detailed flow measurements, an accurate and fair interpretation of the flow topology very close to the wall should not always be based on the level and distribution of heat transfer coefficients, especially for complex flow structures where the validity of *Reynolds analogy* is questionable.

In the present paper, we show experimentally that using highly resolved heat transfer measurements over a relatively narrow range of freestream velocities, where flow topological structures remain essentially constant, fluid flow patterns can be visualised

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by the local determination of the exponent m of Reynolds number. The heat transfer coefficients are evaluated using the transient liquid crystal technique and the evaluated exponent m values are directly compared to oil-flow visualisation experiments. In order to achieve a complex near wall flow structure with longitudinal vortices and associated local heat transfer variations, a vortex generator of delta-wing shape design has been chosen similar to Jacobi and Shah [6], and Gentry and Jacobi [7]. The suggested approach is validated using two additional obstacles of relatively low aspect ratio and fixed on an endwall: a cylinder and a triangle exposed in a crossflow.

2. Experimental details

2.1. Test facility and vortex generator

Fig. 1 shows a schematic representation of the test facility which consists of a two-stage axial flow fan, a bellmouth transition piece, an air heater and a test section where the obstacles are mounted on the base surface of a flat plate with a sharp leading edge profile. The test section consists of a rectangular flow path of $100 \times 100(\mathrm{mm})^2$ and the flat plate is covered with thermochromic liquid crystals in order to visualise the surface temperature. The length of the flat plate is 300 mm and the obstacle is mounted 120 mm downstream from the leading edge. In the present investigation complex flow structures are generated by a full-body tetrahedral element with similar dimensional ratios to Henze et al. [8]. The geometry of the vortex generator (VG) is also shown in Fig. 1. In order to allow clean optical access for the liquid crystal experiments, the channel walls are made out of Perspex. Uniform illumination was provided by two white lights placed on both ends of the flat plate eliminating shadows and reflections.

2.2. Data reduction

The main principle of a transient heat transfer experiment is to observe the time response of the surface temperature to a known step change of the mainstream temperature. In this study, the temperature change was obtained with a heater mesh which was able to increase the temperature of the air at the required level (~30 K), in less than 0.2 s. Power to the metallic mesh was supplied by a 5 kW DC power supply.[1] The temperature evolution was acquired by five K-type thermocouples[2] with exposed junction placed at various streamwise positions, as shown in Fig. 1. The freestream velocity was measured with a thermal anemometer[3] upstream of heater and the indicated velocity was corrected for the hot conditions considering the density variations due to the heating of the flow. The freestream velocity was determined with an overall uncertainty less than 3% over the full range (6.4–13.3 m/s). The freestream turbulence intensity was measured with a hot-wire anemometer[4] upstream of the flat plate providing an area-averaged mean value of 0.5%.

2.3. Transient liquid crystal technique

In a transient liquid crystal experiment, the flow and the model initial temperature (T_o) are subjected to a sudden temperature change and the evolution of a liquid crystal isotherm (T_{LC}) is optically monitored with a CCD camera[5]. This creates a specific correspondence for the detection time of liquid crystals (t_{LC}) and the wall temperature ($T_{G_{max}}$) at that moment. If the thermal conductivity of the model where the liquid crystals are sprayed on is sufficiently low, the heat conduction into the model is limited to a very thin layer near the wall surface (semi-infinite body assumption) and the lateral conduction can be neglected. Therefore, the heat transfer coefficient (h) can be evaluated numerically on a pixel size level by the analytical solution of the 1D transient heat conduction, expressed as [9]:

$$\frac{T_{G_{max}} - T_o}{T_g - T_o} = 1 - exp\left(\frac{h^2 t_{LC}}{\rho c k}\right) er\,fc\left(\frac{h\sqrt{t_{LC}}}{\sqrt{\rho c k}}\right) \tag{2}$$

where ρ, c and k are the density, specific heat and thermal conductivity of the model material. For the evaluation of heat transfer coefficients the maximum green intensity of liquid crystals with an indication temperature of 309.85 K[6] was considered because it is less sensitive to illumination, view angles and reflections [10]. For improved accuracy, liquid crystals were calibrated *in situ* by small variations of the mainstream temperature at steady state conditions using a surface thermocouple. Note also that the liquid crystals are painted 30 mm downstream of the leading edge, and hence, the inclined edge of the flat plate has no influence on the evaluated data and the validity of the 1D heat conduction assumption. Within the temperature levels used in this study, the lateral conduction error was estimated less than 2% [11].

Fig. 2 illustrates a typical temperature change and the uniformity of heating over the complete length of the flat plate. All the thermocouples, from TC1 to TC5, experience the same temperature history, and thus, their average value was considered. Note that the temperature change was fast enough compared to the first liquid crystal appearance times (~4.5 s), and hence, no correction for thermocouple thermal inertia and Duhamel's superposition theorem was applied, as shown by Terzis et al. [12].

The overall local uncertainty in the evaluation of h was always below 13%, where higher heat transfer coefficients are calculated with higher uncertainty similar to Yan and Owen [13]. Table 1 indicates the measured parameters and their individual uncertainty propagation in the final result for a moderate heat transfer coefficient. Note that for the actual repeatability of the experiments, the contribution of material thermal properties should not be considered because it is a systematic error remaining unchanged on repeated experiments.

2.4. Oil and dye flow visualisation

The oil and dye flow visualisation technique was used to visualise the flow pattern on the base surface and around the vortex generator. The mixture was prepared by one part of fluorescein sodium in red colour to twenty parts (by volume) of paraffin oil (viscosity of 1 N s/m^2), similar to Terzis et al. [14]. In the majority of experiments, the concentration of solid pigments in the final mixture was about 0.05 g/cm^3. After the preparation of the mixture, a homogenous thin film was applied on the plate surface by painting it with a soft brush. The air stream, which flows over the surface, modifies the concentration and the homogeneity of the oil film according to the flow conditions very close to the wall. The film was then dried by the airflow and photographed for further consideration. Note that the painted surface was illuminated by a soft, uniform black (UV) light which emits very little visible light. This helps to keep the amount of pigments in the mixture as low as possible eliminating disturbances in the flow.

[1] Agilent 6684A, 40 V–128 A
[2] Omega 5SC Series, 0.076 mm
[3] TSI TA460-A
[4] Dantec MiniCTA
[5] AVT Pike F210C
[6] Hallcrest R36C1