9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE,
AUCKLAND, 8-12 DECEMBER 1986

Experimental & Numerical Determination of Heat Transfer from a Bluff Body in Separated Flow

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ABSTRACT

This paper qualitatively compares experimental and numerical studies of the temperature field and heat transfer occurring with separating and reattaching flow over a heated blunt flat plate when an applied sound field is used to order the flow.

A Schlieren optical system, used to visualise the instantaneous temperature gradients occurring in the flow field, is briefly described. A numerical model of the flow and heat transfer is outlined and qualitative comparisons are made between the experimental and computed instantaneous temperature fields. The influence of the large scale flow structures on the temperature field is observed and it is concluded that the results of the numerical model are in agreement with the experimental observations.

INTRODUCTION

Experimental work at the CSIRO Division of Energy Technology on the influence of sound on separating and reattaching flow over a blunt flat plate (Parker & Welsh 1983) suggested that the resulting vortex structures may be increasing the rate of heat transfer from the surface. Ota & Kon (1979) showed that increases in time averaged heat transfer rates with separated and reattached flow over a flat plate was a function of the size of the separation bubble which varied with the shape of the leading edge. Experimental work by Cooper et al (1986) found that shortening the length of the separation bubble with an asymmetric sound field applied to the plate also resulted in increases in the time averaged heat transfer rate which were a function of the bubble length. In particular, it was found that there is a generally lower Nusselt number within the separation bubble near the leading edge, a maximum at reattachment that increases with increasing sound pressure level (reducing bubble length) and a general decrease further downstream.

It was evident that a true understanding of the flow and heat transfer mechanisms would result from complementary numerical and experimental programmes studying the instantaneous flows and temperatures. It also became apparent that though a sound field was not a practical way of augmenting heat transfer, it could be used to control the flow and make it more amenable to study. The basic function of an asymmetric sound field is to introduce velocity perturbations at the leading and trailing edges which are at right angles to the mean flow direction.

There are various methods of experimentally obtaining instantaneous temperatures in rapidly fluctuating flows, but deriving an instantaneous temperature field in two dimensions presents experimental problems. Because experimental measurements of the instantaneous velocity field in the region of the separation bubble appear to confirm the numerical predictions (Welch et al 1986), the decision was taken to use a Schlieren optical system to visualise the thermal gradients in the flow in anticipation of their qualitatively agreeing with the temperature fields predicted by the numerical model.

The following sections describe the experimental apparatus and the numerical model and qualitatively compare the results of the Schlieren visualisation studies with numerical model predictions.

TEST APPARATUS AND PROCEDURE

The test apparatus was essentially the same as used in the steady state investigation (Cooper et al 1986) and was adapted to incorporate a simple Schlieren optical system (see Fig 1, p.62 of Cooper et al 1986).

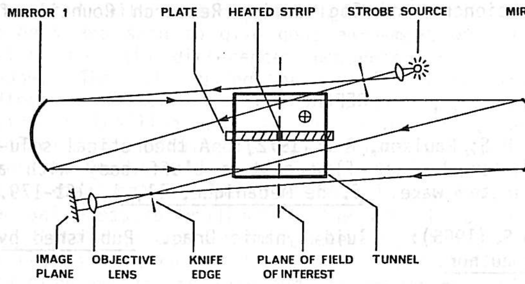

Fig 1: Schematic diagram of Schlieren system

The flat plate of span 300mm, thickness 13mm and chord 120mm was placed centrally at zero incidence in the working section of a small, open jet wind tunnel of dimensions 244mm X 244mm at outlet. Because a Schlieren system detects density gradients existing at all points along a collimated beam, it was necessary to achieve a narrow spanwise thermal field by placing a 2mm wide heater strip of 76×10^{-6}m thick stainless steel around the plate at the mid-span position. Electrical connections to a stabilised ac supply were made at the trailing edge. The heater strip approximated a constant heat flux surface with negligible radiant heat transfer.

An asymmetric acoustic field was generated by speakers placed above and below the plate which were driven in antiphase through a two channel amplifier connected to an audio oscillator. The fences that were used in previous investigations to ensure a two dimensional sound field over a span of about 125mm (Cooper et al 1986) were not used in this work because of their interference with the optics of the Schlieren system.

The basic elements of the Schlieren system are a source of light, two front surfaced mirrors, a knife edge and an objective lens to focus on the plane of interest (the heated strip). The source was a strobe flash unit which could be driven synchronously with the sound, at sub-multiples of the frequency or asynchronously to observe the apparent motion of the temperature gradient field.

The experimental work reported here was conducted at a sound pressure level of 115dB at the middle of the plate, a frequency of 135Hz, an ambient temperature of approximately 20°C and air approach velocities of 10m/s and 2m/s, giving sound Strouhal numbers of 0.18 and 0.88 and Peclet numbers of 6140 and 1230 respectively. The Strouhal number is the product of the sound frequency and plate thickness divided by the flow velocity, while the Peclet number is the product of the Reynolds nunber based on plate thickness and the Prandtl number. Limitations on the minimum frequency that could be achieved with the specialised speakers precluded experimental observations at a Peclet number close to 1000 and a Strouhal number of 0.2. The Strouhal and Peclet numbers of 0.18 and 6140 were chosen to coincide approximately with the experimental work of Welch et al (1986) while the values at 2m/s provide Schlieren images at a Peclet number approaching the upper values which can be used currently in the numerical model. Photographs of the Schlieren image were taken using a single, high intensity flash, which could be triggered at any desired phase angle from the sound field. Zero phase angle was taken to be at minimum acoustic pressure above the top surface and zero acoustic velocities at the leading and trailing edges.

DESCRIPTION OF THE NUMERICAL MODEL

A combination of approaches was adopted to model the forced convective heat transfer process near the leading edge of a square leading edge plate. A discrete-vortex model was used to predict the velocity field for the high Reynolds number flow and the concomitant solution of the energy equation was obtained via a finite-difference approximation.

Discrete-vortex Model

The plate was assumed to be semi-infinite with a square leading edge aligned symmetrically to the two-dimensional flow.

The primary introduction of vorticity into the flow takes place at the leading edge corners of a plate. Analysis was restricted to the top shear layer, which was replaced by discrete line vortices. The fluid was assumed to be inviscid, incompressible and irrotational everywhere except at the positions of the line vortices. The condition of zero normal velocity at the plate surface was met by introducing image vortices; the positions of these image vortices were found by mapping the plate surface to the real axis of a different plane using a Schwarz-Christoffel transformation. The strengths of the vortices entering the flow were found using a scheme adopted by Nagano et al (1982) in which the velocity of the outer edge of the shear layer was determined at a fixed point near separation; the Kutta condition then determined the initial vortex positions. The vortices were advected according to the local velocity resulting from the irrotational flow and the remaining vortices.

The net rate of vorticity shedding along the plate is governed by the tangential surface pressure gradients (Morton 1985). Self-consistency in the model was achieved through the annihilation of primary vorticity downstream of separation; an iterative scheme was employed to achieve a balance between time-mean rates of vorticity generation and surface pressure gradients. Further description of the model is provided in Thompson and Hourigan (1985).

Finite-difference Approximation of the Energy Equation

At each time-step, the fluid velocity determined by the discrete-vortex model was substituted into the energy equation; buoyancy and radiation effects were neglected. The energy equation was then solved using a flux-limiting scheme (Zalesak, 1979). The higher order component was QUICKEST (Leonard, 1979), an explicit third-order upstream differencing scheme for the advection terms, with an extension for the truncation time difference terms in a manner similar to Leith's method (1965). A donor cell method constituted the lower order part of the scheme, for which a compressed mesh of size 51 x 31 was used.

The boundary conditions adopted were: constant heat flux at the plate surface; ambient temperature at the boundary away from the plate surface; zero temperature gradients at the outflow boundaries. The vectorized code was run on a Cyber 205 computer.

RESULTS AND DISCUSSION

A typical Schlieren photograph of flow over the heated plate without sound and a Peclet No. of 1230 is shown in Fig. 2. The lower flow rate has been chosen here as it better illustrates features which are not as evident at higher velocities. The temperature of the heated strip was approximately 75°C. Due to possible loss of detail in reproducing the photographs, the outlines of the structures have been indicated by dashed lines.

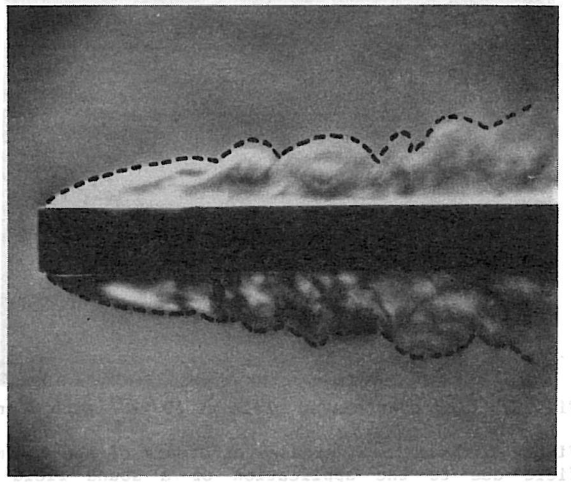

Fig. 2: Flow over heated plate at 2 ms^{-1} without sound

The large temperature gradients which occur within a few millimetres of the surfaces appear as very light layers on the top surface. There are essentially no temperature gradients in the background which has a uniform optical density, while regions with positive gradients (temperature decreasing in the positive y direction normal to the plate surfaces) appear brighter than the background. Darker regions signify decreasing temperature in the negative y direction. The presence of large scale structures is evident from the temperature gradients but a clearly defined separation bubble is not as apparent as with smoke visualisation of the flow field (Parker & Welsh 1983). This is to be expected as the Schlieren photograph is indicating temperature gradients only in the y direction. Of particular interest are the reverse temperature gradients that can be clearly seen as dark regions on the top surface (light on the bottom) which are manifest in the "cores" of the structures. This suggests the exchange of heat with cooler fluid from the mainstream as warmer fluid is drawn away from the heated surface, around a vortex structure and then returned to the surface in a cooled state. Although some interpretation has been possible in this no sound case, two drawbacks emerge: firstly, at the higher flow velocity, it is difficult for the optics to discern flow structures; secondly, the random nature of vortex shedding poses extreme difficulties in relating observed thermal structures at any particular instant to the flow structures determined by other means. The use of sound overcomes these difficulties.

A Schlieren photograph of the effect of sound is shown in Fig.3 at a Peclet No. of 6140, a sound pressure level of 115dB and a Strouhal No. of 0.18. The approximate plate temperature was 55°C for these conditions. The flash was triggered 180° lagging the sound pressure field so that there is maximum acoustic pressure above the top surface and zero acoustic velocity at the leading edge about to go negative. The computed vortex velocities and isotherms for Peclet numbers of 100 and 1000 and a Strouhal number of 0.2 shown in Figs. 4 and 5 indicate the form of the structures and temperature gradients observed. At present the numerical model is limited to a maximum Peclet number of about 1000 due to computational time restrictions. However, qualitative comparisons between these and the experimental results at 6140 will be valid because the dominant vehicles of transport, the large scale structures, are insensitive to viscous effects in the high Reynolds number regime. Indeed, the predicted large scale patterns in the thermal field are seen to be similar for the two different Peclet numbers.

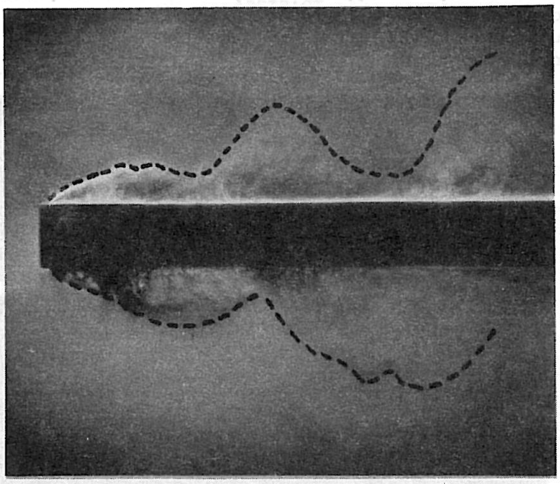

Fig. 3: Flow over heated plate at 10 ms^{-1} with sound

Figure 3 shows the increased coherency of the thermal field due to the application of a sound field at 135 Hz. The initially smooth shear layers bounding the instantaneous separation bubbles are highlighted by large temperature gradients; these shear layers result from boundary layers on the heated front face of the plate separating at the corners. (The appearance of the shear layers a short distance downstream from the leading edge in Fig. 3 is due to parallax error resulting from the camera being centred at mid-chord of the plate.) The apparent separation bubble on the top surface has already "ejected" a vortex while that on the lower surface (which is 180° out of phase) is beginning to grow as the acoustic velocity becomes more negative. This is precisely the phenomenon reported by Parker and Welsh (1983) from flow visualisation studies. Larger structures are evident downstream of the separation bubbles. The size and spacing of these structures is consistent with the pairing process measured with hot wires (Welsh et al, 1986).

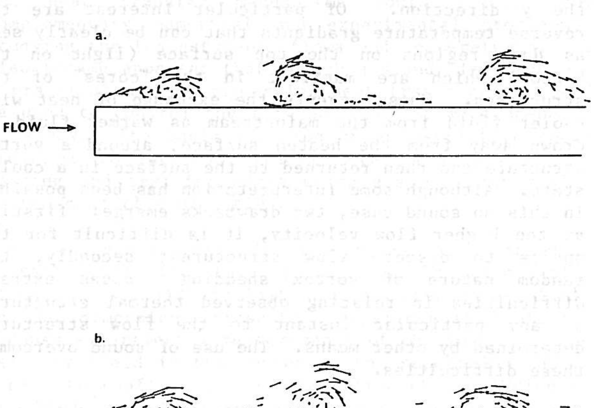

Fig. 4: Computed velocities of the elemental vortices with sound

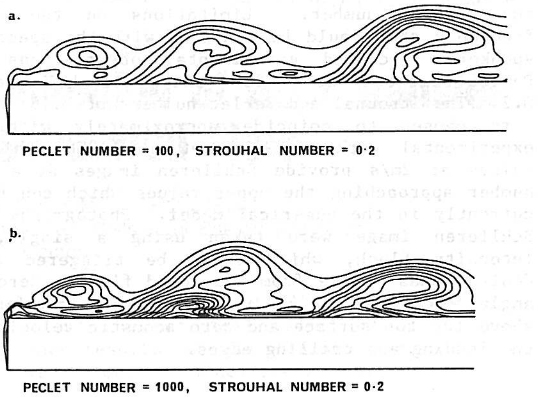

Fig. 5: Computed isotherms for flow over heated plate with sound

Variations in vertical thermal gradients can be seen in all structures in Figs. 3 and 5; reverse gradients are particularly noticeable within the separation bubbles close to the leading edge. The numerical model demonstrates the very strong temperature gradients close to the surface. It appears to successfully model the experimentally observed reversed temperature gradients perpendicular to the surface underneath the leading edge of the vorticose structures.

CONCLUSIONS

A Schlieren optical system has been successfully used to visualise the instantaneous temperature gradients in separating and reattaching flow over a bluff body. Observations of temperature gradients at a low Peclet Number and no sound clearly showed large scale structures and pointed to non-uniformities in thermal gradients over individual structures.

The application of a sound field resulted in an increase in the coherency of the flow, allowing the flow structures to be readily discerned and compared with the results of the numerical model. The observed vertical temperature gradients qualitatively correspond to those predicted by the numerical model.

ACKNOWLEDGEMENTS

The authors wish to thank N.B. Hamilton for his photographic work. Dr M.C. Thompson gratefully acknowledges the support of a CSIRO Postdoctoral Award.

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