NUMERICAL SIMULATION OF SEPARATED AND REATTACHED FLOWS: EFFECT OF ACOUSTIC FIELD ON HEAT TRANSFER

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Introduction

Augmentation of the Nusselt number along a plate is found to occur when the flow is made to separate from the leading edge (Ota and Kon [1]). Further augmentation results when the mean reattachment length is decreased by changing the plate nose geometry (Ota and Kon [2]) or through application of an acoustic field. In fact, the time-mean local Nusselt number along the plate is chiefly a function of the mean reattachment length and is not sensitive to the perturbing mechanism (Cooper et al [3]). However, the application of sound is especially useful as an experimental technique in that it orders the large-scale vortex structures that are shed from the separation bubble (Parker and Welsh [4]). The increased coherence of the flow allows the use of conditional sampling with pressure probes, thermocouples and laser Doppler anemometers to construct an 'instantaneous' picture of the velocity and temperature fields. One aim of the present numerical work is to provide also the instantaneous fields, which can be used as guidelines for future experimental investigations.

Outline of the Numerical Model

The flow considered here is that past a rigid, two-dimensional, semi-infinite heated flat plate, which is aligned with a square leading edge normal to the flow. The flow at upstream infinity is taken to be of uniform velocity and temperature. The fluid is assumed to be inviscid, incompressible and irrotational everywhere except at points where simple inviscid line vortices are located. Attention is focussed on the shear layer separating from the top leading edge corner. The effect of the vorticity generated at the lower leading edge corner is assumed to be negligible.

The discrete-vortex model replaces the continuous sheet of vorticity entering the flow from the leading corner of the plate by a distribution of elemental line vortices. Vortices that recirculate upstream of the mean reattachment have their strengths reduced by a set fraction at each step to account for the generation of vorticity of opposite sign at the plate surface. In line with Morton [5], the amount of vorticity generated is matched to its generating mechanism - the tangential surface pressure gradient. A transverse fluctuating flow representing the acoustic field is also incorporated into the model.

The energy equation is solved using QUICKEST (Leonard [6]). This explicit scheme uses third order upstream differencing for the advection terms. The method approachs third order accuracy in both time and space as the Peclet number approaches infinity (but for a constant flow velocity).

A more detailed description of the discrete-vortex model and the finite-difference scheme used is contained in [7].

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Results

A major reason for looking at this problem is to identify mechanisms responsible for changes in the heat transfer characteristics as the mean reattachment length is decreased through the application of sound. An important characteristic is the Nusselt number at the plate's surface. Figure 1 shows the mean Nusselt number along the surface of the plate for the following ratios of the acoustic particle velocity u_s to the approaching flow velocity v_∞: $u_s/v_\infty = 0$, 0.1 and 0.3. (The averaging is done over 1000 timesteps or 10 acoustic cycles. The Peclet number is 20). The mean separation bubble length shortens from 9H through 6H to 4H as the acoustic particle velocity is increased from zero through $0.1v_\infty$ to $0.3v_\infty$. (Here, H is the semi-thickness of the plate). The comparison of the curves indicates that an increase in the sound level results in a substantial increase in the peak value of the time-mean local Nusselt number.

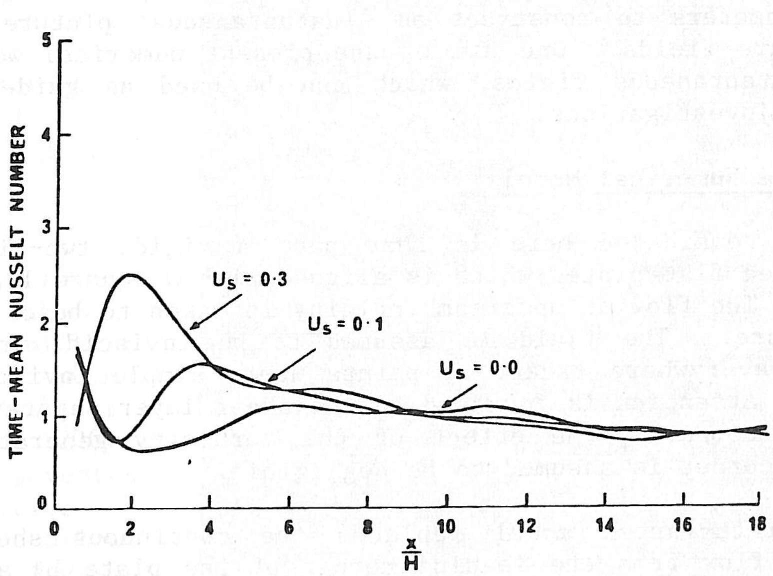

Figure 1. Predicted mean local Nusselt number for three different levels of acoustic perturbation.

Perhaps of more practical significance, reduction of the mean reattachment length is found to lead to a considerably greater time-mean Nusselt number averaged spatially over the plate. A quantitative comparison of the heat transfer characteristics at different sound levels can be made by averaging the Nusselt number over the first 10H of the length of the plate (this being typical of the plate lengths found in commercial heat exchangers) The values for the (spatially-averaged) time-mean Nusselt numbers are 0.95, 1.2 and 1.5 respectively. Thus the results indicate that by decreasing the reattachment length a substantial increase (up to 60% here) in the heat transfer can be achieved. This predicted trend is precisely in line with that found in experimental investigations (Cooper et al [3], Ota and Kon [2]).

An important feature of the present model is the prediction of the instantaneous flow. This allows further insight into the mechanisms responsible for the augmentation of the heat transfer rate. A 16mm movie film showing some of the numerical results has been made of the present simulations. Here, a 'snapshot' from the movie film is included in Figure 2 that characterise the flow structures and thermal field for a high sound case. The increased coherence of the flow through the locking of the vortex shedding to the acoustic field is clearly evident. Distortion of the isotherms near the large-scale vortex structures is seen. The local Nusselt number is found to be maximal immediately downstream of a vortex and to be minimal just upstream.

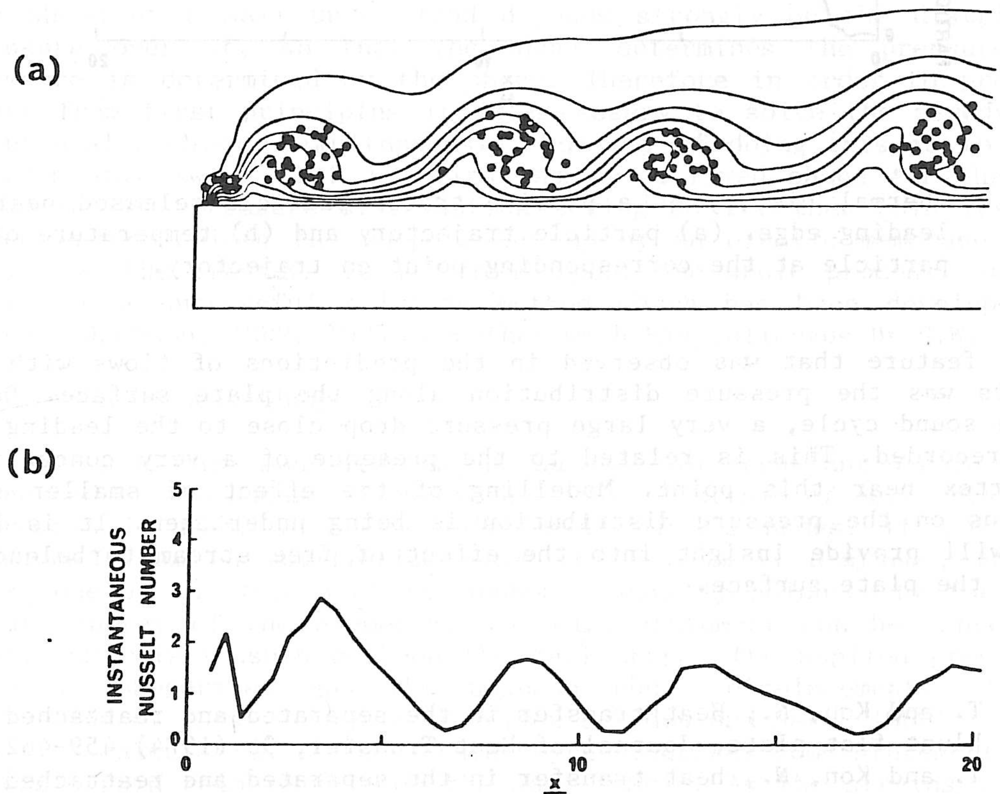

Figure 2. (a) Characteristic instantaneous isotherms for $u_s = 0.3v_\infty$. Small circles indicate positions of elemental vortices.
(b) Instantaneous local Nusselt number against distance along the plate surface.

The history of the temperature of a tracer particle released near the leading edge corner is shown in Figure 3. The repeated cooling and heating of the particle as it is moved towards and away from the plate's surface by the large-scale vortex structures is demonstrated.

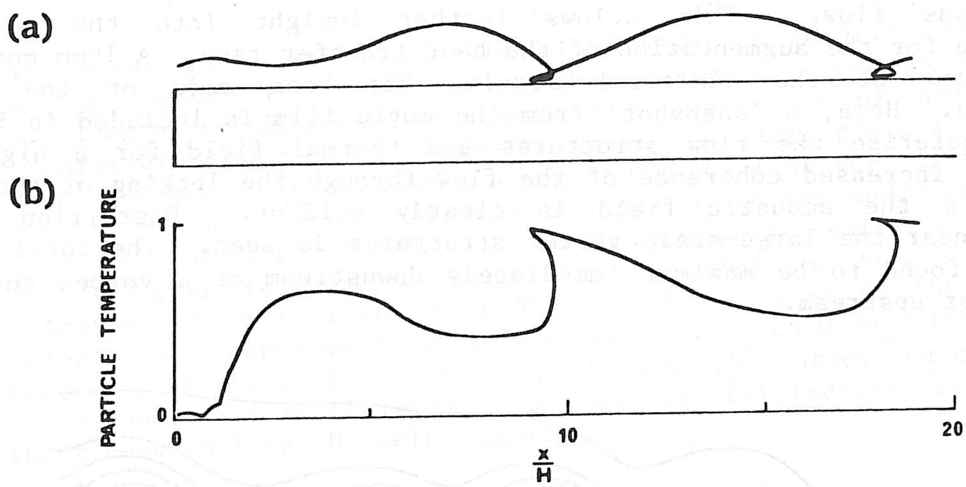

Figure 3. Thermal history of a passive tracer particle released near the leading edge. (a) particle trajectory and (b) temperature of the particle at the corresponding point on trajectory.

Another feature that was observed in the predictions of flows with high sound levels was the pressure distribution along the plate surface. During part of the sound cycle, a very large pressure drop close to the leading edge corner is recorded. This is related to the presence of a very concentrated growing vortex near this point. Modelling of the effect of smaller scale perturbations on the pressure distribution is being undertaken. It is hoped that this will provide insight into the effect of free stream turbulence on suctions on the plate surface.

References

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