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THE EFFECT OF SOUND ON FORCED CONVECTION FROM A FLAT PLATE

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SUMMARY This paper reports on the experimental investigation into the effect of a sound field on the time averaged heat transfer from a flat plate with separated and reattached flow. Increasing the pressure level of an asymmetric acoustic field decreases the length of the separation bubble and increases the maximum heat transfer coefficient occurring at reattachment and the average coefficient over the plate. The influence of the sound field was apparent at sound pressure levels as low as 100 dB (re 20 μPa) while sound frequency variation had little effect at free stream velocities of 20 ms^{-1} or more. The reattachment Nusselt number was found to correlate simply with reattachment Reynolds number as found previously from experiments in which the reattachment length was varied without sound. Downstream of reattachment, the local heat transfer coefficient decreased with increasing sound pressure level, suggesting the presence of flow structures in the boundary layer which reduce the transport of heat between the surface and the free stream.

NOMENCLATURE

Nu_R	Nusselt number at reattachment, based on reattachment length
Nu_x	Nusselt number at distance x from leading edge
$\bar{Nu}$	Average Nusselt number over plate surface
Pr	Prandtl Number
Re_R	Reynolds number based on reattachment length
Re_x	Reynolds number based on distance x from leading edge
$\bar{Re}$	Reynolds number based on plate length in flow direction

1 INTRODUCTION

The influence of an asymmetric sound field on the separated and reattached flow over flat plates with square leading edges and various chord to thickness ratios has been reported by Parker and Welsh (1983). They found that when sound was applied, the leading edge shear layers reattached closer to the leading edge and the oscillations in the length of the separation bubble occurred at the applied sound frequency, generating patches of concentrated vorticity in the boundary layers.

The effect of sound on heat transfer in both free and forced convection has been extensively studied (see Richardson (1967)) particularly with regard to circular cylinders. Peterka and Richardson (1969) examined the effects of intense sound fields on the flow around a cylinder and on the mechanism of heat transfer in separated flows. One of their conclusions was that heat transfer from a body under separated flow can be increased if a sound field is applied at a frequency chosen to match an instability frequency natural to the separated shear layer.

There is a large body of work reported on the heat transfer in separated and reattached flows for a variety of configurations, including forward and backward facing steps, surface roughness elements and abrupt expansions or contractions in tubes (Fletcher, Briggs and Page (1974)). Recently, Ota and Kon (1974), Ota and Itasaka (1976) and Ota and Kon (1979) have reported the results of their experimental studies on the separated and reattached flow over flat plates with different nose shapes and its influence on the heat transfer. They found that though the reattachment length was dependent on the nose shape, the correlation between the reattachment Nusselt number and Reynolds number was independent of nose shape when the reattachment length was used as the reference length. They also found that increases in heat transfer above that for an ordinary turbulent boundary extended far downstream from the point of reattachment.

This paper presents the results of initial experiments on the influence of an asymmetric acoustic field on the heat transfer from a flat plate with a square leading edge. The variables considered were free stream velocity, sound pressure level and sound frequency.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

The test apparatus was a small open-jet wind tunnel containing an instrumented flat plate with a square leading edge around which the sound pressure level and frequency could be varied independently, see Figure 1. The working section was 244 mm x 244 mm at outlet, with a uniform mean velocity in the jet within ±0.5% and a low longitudinal turbulence intensity of 0.2%. Major spectral components were between 0.1 Hz and 150 Hz.

The test plate of span 300 mm, thickness 13 mm and chord 120 mm was placed centrally in the working section at zero incidence to the jet, with the leading edge 290 mm from the outlet. Local time averaged heat transfer coefficients were derived from measurements of local variations in time averaged temperatures at mid span over the top surface of the plate. The surface of the plate was a constant heat flux surface consisting of 76 μm thick stainless steel shims connected in series and wrapped around a wooden core with 1 mm spacing between each shim. Local temperatures were measured at 10 mm intervals along the chord at the mid span position from the leading to the trailing edge with fine 40 g copper/constantan thermocouples attached to the underside of the centre stainless steel shim. Another thermocouple was placed at the centre of the leading edge and two were located on the underside of the plate to check on the symmetry of heat transfer.

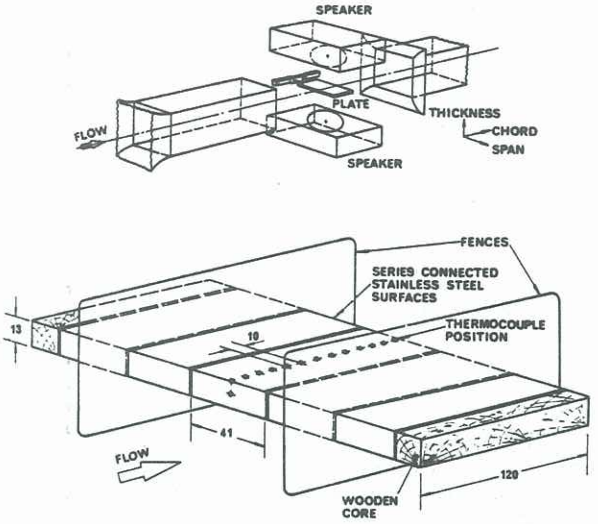

Figure 1 Schematic diagram of experimental equipment

A stabilized AC current was used to heat the stainless steel sheet and a data logger measured each thermocouple signal over 15 line cycles.

An asymmetric acoustic field was generated by loudspeakers above and below the plate, connected in antiphase through a two channel power amplifier whose signal came from an audio oscillator. The relative phases and levels of each channel were adjusted at each frequency so that zero acoustic pressure existed at all times in the plane of the plate at the leading and trailing edges and maximum acoustic pressure existed at the mid-chord position on the top and bottom surface of the plate. Sound pressure levels reported in this work refer to measurements at the mid-chord position in the centre of the span taken with a probe microphone in the absence of air flow. The sound field around the plate is similar to a β-mode acoustic resonance when a plate is enclosed in a duct (Parker (1967)). Fences were placed around the heater plate 127 mm apart to ensure a two-dimensional sound field.

Local heat transfer coefficients were derived from the constant heat flux and the differences between the local temperatures and the air temperature upstream of the contraction, after allowing for radiation losses. Air velocities were determined by measuring the static pressure differences across the contraction upstream of the open jet section. Air properties were evaluated at the upstream temperatures.

The range of variables considered were approach velocities from 10 to 40 ms^{-1}, sound pressure levels of 100 dB to 122 dB (re 20 μPa) and frequencies from 400 to 1200 Hz in steps of 200 Hz. For all tests, a constant electrical input gave a heat flux of about 1400 Wm^{-2} and non-convective losses amounted to less than 1.5%. All tests were conducted under steady state conditions.

3 RESULTS AND DISCUSSION

Typical results of the time averaged local heat transfer coefficients along the plate as a function of free stream velocity and sound pressure level at a frequency of 400 Hz are shown in Figure 2. Also included is the heat transfer coefficient at the centre of the leading edge.

The local heat transfer coefficient decreases from the centre of the leading edge to a minimum value approximately 10 mm from the leading edge. The precise value and location of this minimum cannot be determined because of the limited spatial resolution

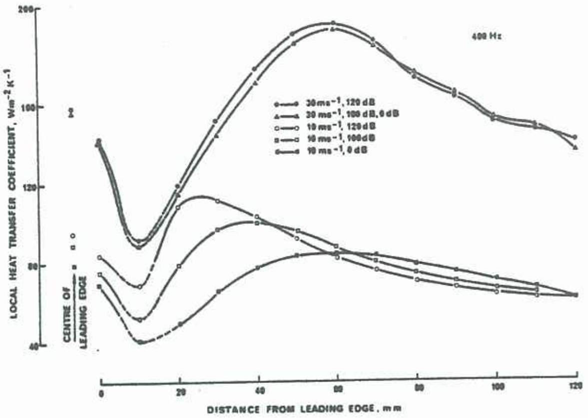

Figure 2 Local heat transfer coefficient as a function of velocity and sound pressure level at 400 Hz.

of the temperature measuring points. The heat transfer coefficient then rises to a maximum whose value and position depends primarily on the free stream velocity and the sound pressure level. The position of the maximum heat transfer coefficient coincides with the mean position of reattachment of the leading edge shear layer as found by Ota and Kon (1979) and confirmed in this work by inspection of the movement of water droplets on the plate surface. In the absence of sound, the point of reattachment was almost independent of the free stream velocity for the low turbulence intensity of the stream and occurred between 4 and 5 plate thicknesses downstream from the leading edge. This is in agreement with the findings of Lane and Loehrke (1980), Ota and Kon (1979) and Ota and Itasaka (1970).

Increasing the sound intensity from 0 to 120 dB for a free stream velocity of about 10 ms^{-1} is seen to shift the reattachment point towards the leading edge and to increase the maximum heat transfer coefficient. There is no significant movement of the point of minimum heat transfer coefficient, within the limits of spatial resolution. At 30 ms^{-1}, there is essentially no increase in the local heat transfer coefficient as the sound pressure level is increased from 0 dB to 100 dB and only a small increase from 100 dB to 120 dB.

Some distance downstream of reattachment, the local heat transfer coefficient decreases, at a constant free stream velocity, with an increase in sound pressure level. This effect suggests that at higher sound pressure levels the transport of heat away from the fluid adjacent to the surface is inhibited. Thus, for a constant heat flux from the surface, the fluid temperature increases. This in turn results in a higher surface temperature and a low local heat transfer coefficient. Parker and Welsh (1983) have noted that the sound field generates patches of vorticity in the boundary layer along the plate and it is suggested that these flow structures inhibit the transport of heat away from the fluid layer adjacent to the surface. The results of Ota and Kon (1979), in which the separation bubble length altered with changes in leading edge shape, show a similar reversal of local heat transfer coefficients some distance downstream of the separation bubble. This reinforces the similarity between the effect of sound and leading edge shape on the flow and heat transfer on the plate.

On the assumption that the time averaged maximum heat transfer coefficient occurs at the time averaged position of reattachment of the shear layer, the length of reattachment from the leading edge was derived from the measurements by curve fitting in the region of the maximum and differentiating. The non-dimensional reattachment length is shown in Figure 3 as a function of the sound pressure in Pa for all free stream velocities and sound frequencies of 400, 800 and 1200 Hz. It is evident that the reattachment length is dependent on frequency at high sound pressures for low free stream velocities and has a reduced effect for other combinations of sound pressure and velocity. For velocities of 20 ms^{-1} and above, there is no discernible effect of frequency. The reattachment length is also fairly insensitive to sound pressures above about 2 Pa, particularly at the higher free stream velocities.

The correlation between the reattachment Nusselt number Nu_R and the Reynolds number Re_R based on the reattachment length is shown in Figure 4 and a least squares fit to the data gives the following expression:

$$Nu_R = 0.0699\ (Re_R)^{0.751}$$

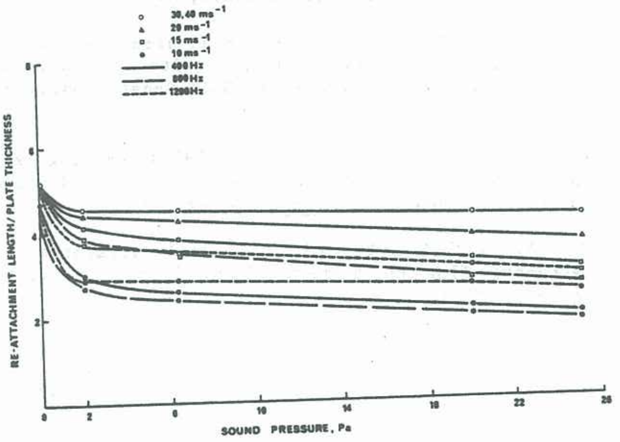

Figure 3 Non-dimensional reattachment length as a function of sound pressure, frequency and air velocity

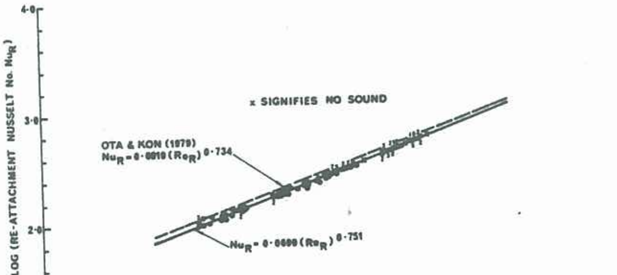

Figure 4 Reattachment Nusselt number as a function of the reattachment Reynolds number

Also shown is the correlation found by Ota and Kon (1979) based on results from experiments in which the reattachment length varied because of the shape of the leading edge of the plate. There is obviously excellent agreement which highlights the significance of the reattachment length as a correlating variable. Kiya and Sasaki (1983) showed experimentally that the length of the separation bubble on a blunt flat plate reduces significantly with increasing turbulence intensity. It is therefore reasonable to consider that the effects of turbulence intensity and the influence of the characteristics of the sound field in shortening the length of the separation bubble are similar. This suggests that the ratio of acoustic particle velocity (which is proportional to the sound pressure and inversely proportional to the frequency) and the free stream velocity would correlate with the length of the separation bubble and hence the heat transfer coefficient at the point of reattachment. Unfortunately, we have not been able to correlate the data presented in Figure 3 to reveal a simple relationship between reattachment length and the sound and flow variables.

A plot of the local Nusselt number Nu_x as a function of the Reynolds number Re_x based on the distance from the leading edge is shown in Figure 5 for a free stream velocity of 15 ms^{-1} with no sound and sound of 120 dB at 400 Hz. Also shown is a standard correlation for forced convection heat transfer in a turbulent boundary layer over a flat plate. The significant influence of the separated flow on the heat transfer coefficient in the region of reattachment can be seen. The heat transfer coefficient for some distance upstream of reattachment is also above that which would prevail in the normal turbulent flow situation. Ota and Kon (1979) noted that the elevated heat transfer coefficients resulting from separated and reattached flow persisted for a long distance downstream of the reattachment point. At higher sound pressure levels the heat transfer approaches the normal turbulent boundary layer case because of the reduced transport of heat away from the surface.

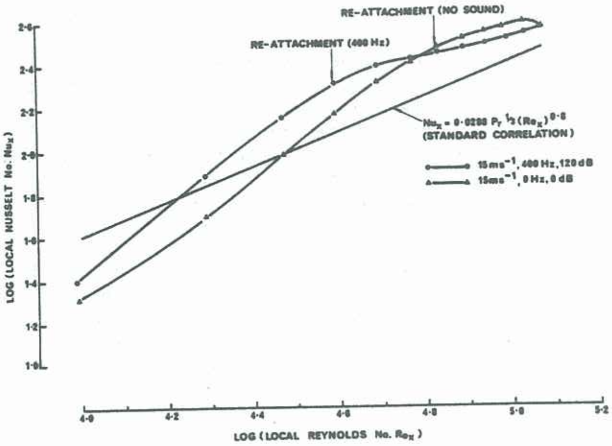

Figure 5 Local Nusselt number as a function of Reynolds number for a velocity of 15 ms^{-1} with no sound and sound of 120 dB at 400 Hz

The variation of the average heat transfer coefficient over the surface with velocity and sound pressure level is of interest from an applications point of view. Figure 6 shows the average Nusselt number $\overline{Nu}$ over the surface as a function of the Reynolds number $\overline{Re}$ based on the plate length in the flow direction. Results are shown for no sound and sound pressure levels of 100, 110, 120 and 122 dB at a frequency of 400 Hz. The correlation shown for a turbulent boundary layer on a flat plate assumes that it is turbulent from the outset.

At a Reynolds number of about 80,000 the average Nusselt number for separated and reattached flow over the plate with no sound is about 25% greater than that for a turbulent boundary layer, while the sound field increases the average Nusselt number to be from 35% to 40% above the turbulent value. At a Reynolds number of about 300,000, the average Nusselt number is about 7% above the turbulent value, rising to about 12% when the sound field is applied.

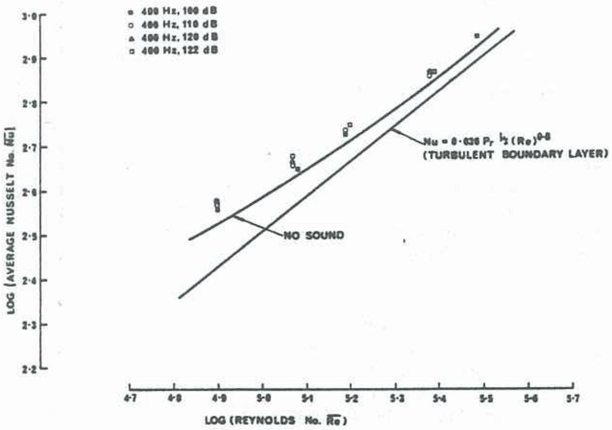

Figure 6 Average Nusselt number over plate as a function of Reynolds number based on plate length for no sound and sound of 400 Hz at sound pressure levels of 100, 110, 120 and 122 dB

4 CONCLUSIONS

The heat transfer in separated and reattached flow on a flat plate with a square leading edge has been measured when an asymmetric sound field is applied to the plate. A low free stream turbulence intensity was used.

The effect of the sound field is to shorten the time averaged reattachment length and increase the maximum time averaged heat transfer coefficient which occurs at reattachment. The reattachment bubble length decreased with increased sound pressure and decreased free stream velocity while variation of frequency only had an effect at velocities below 20 ms^{-1} for sound pressure levels up to 122 dB.

Downstream of the reattachment point, the local heat transfer coefficient decreases with increasing sound pressure level. A better understanding of this phenomenon is likely to result from a detailed study of the fluid mechanics and heat transfer downstream of reattachment.

It was found that the reattachment Nusselt number could be simply correlated with the reattachment Reynolds number over the range of sound pressure levels sound frequencies and free stream velocities. The resulting correlation was essentially the same as that found by others who varied reattachment lengths using different leading edge shapes. A simple correlation between reattachment length and the characteristics of the sound field has not been found.

The average heat transfer coefficient over the plate with separated and reattached flow and an applied asymmetric sound field was compared with that for a normal turbulent boundary layer. It was found that the average heat transfer coefficient was increased due to the separated flow/sound field combination by about 40% at a Reynolds number of 80,000, decreasing to about 12% at a Reynolds number of 300,000.

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