The effects of sound on forced convection over a flat plate

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An experimental investigation into the effects of a sound field on the time-averaged heat transfer from, and drag on, a flat plate with a square leading edge having separated and reattached flow is reported. Increasing the sound 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 drag coefficient on the plate in the absence of sound increased slightly with free stream velocity. 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 by changing the leading edge geometry or angle of attack of the plate.

Keywords: *sound field effects, forced convection, heat transfer, separated flow, reattached flow, drag, airflow over flat plates*

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[1]. They found that when sound was applied, the leading edge shear layers reattached closer to the leading edge and 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[2] particularly with regard to cylinders. Peterka and Richardson[3] 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[4]. Recently, Ota and colleagues have reported the results of a series of experimental studies on the separated, reattached and redeveloped flow over flat plates with blunt leading edges[5-7]. In one study in which the separation bubble size varied with the nose geometry, Ota and Kon[7] found that 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 a fully developed turbulent boundary extended far downstream from the point of reattachment.

Recently, McCormick *et al*[8] reported on the heat transfer to separated flow regions from a constant temperature surface on a flat plate with a chord to thickness ratio of 4:1 at various angles of attack. They found that the relationship between the reattachment Nusselt and Reynolds numbers was independent of the angle of attack when the reattachment length was used as the length scale. Their results indicated heat transfer coefficients over the plate surface were up to 50% higher than those found by Ota and Kon[7]. Using tufts to indicate the reattachment position they reported a reattachment length 3.5 model thicknesses downstream of the leading edge compared to the 4 to 5 values found by Ota and Itasaka[6] and Sam *et al*[9].

Only limited information is available on the drag on flat plates with square leading edges and most of this is restricted to bluff bodies with chord to thickness ratios (L/t) of no more than 2 (see, for example, Delany and Sorensen[10] and Gartshore[11]). Hoerner[12] presents some limited data on the drag coefficient C_D as a function of L/t up to values of about 6, which shows that C_D decreases from about 2.0 for $L/t<2.5$ to about 1.0 for $L/t>4$. In a recent study, Jancauskas[13] reported drag coefficients for prisms with a range of rectangular cross-sections with L/t from 0.25 to 16.07, turbulence intensities from smooth flow to 12.5%, and angles of attack from 0° to 15°. For $L/t=10$ and zero angle of attack, values of $C_D=1.4$ were found for smooth flow and turbulence intensities of 5% and 12.5%. All testing for $L/t=10.0$ was done at a Reynolds number (based on model thickness) of 2×10^4.

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

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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 Fig 1). The working section was 244 mm × 244 mm at outlet, with a uniform mean velocity in the jet within $\pm 0.5\%$ and a longitudinal turbulence intensity of 0.2%. Major spectral components were between 0.1 Hz and 150 Hz.

For heat transfer measurements a 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 shown in Fig 1 was essentially 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 to form a conductor of about 1.3 m total length with a resistance of approximately 0.5 Ω. The stainless steel surface had a measured thermal emittance of 0.15 and its rate of change of resistance with temperature was estimated to be less than $2.5 \times 10^{-4}\,\Omega\,K^{-1}$. For all tests reported here the plate temperature was between 20°C and 40°C, indicating that the maximum variation in heat flux across the plate due to temperature effects would generally be less than 1%. 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 copper/constantan thermocouples made from 0.08 mm diameter wire 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. A stabilized ac supply 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 driven by 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 midway between the upper and lower surfaces. Maximum acoustic pressure existed at the mid-chord position on the top and bottom surfaces of the plate. Sound pressure levels reported in this work refer to measurements at the mid-chord position on the plate surface 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[14]. Fences were placed around the heater plate 127 mm apart to ensure a two-dimensional sound field (Fig 1).

For the measurement of drag forces the heat transfer plate was replaced by a specially constructed aluminium plate of the same dimensions located at the same position in the open jet. Because of the small total forces involved, particularly at lower velocities, drag forces on the fences had to be isolated from the measurements. This was accomplished by fixing the fences

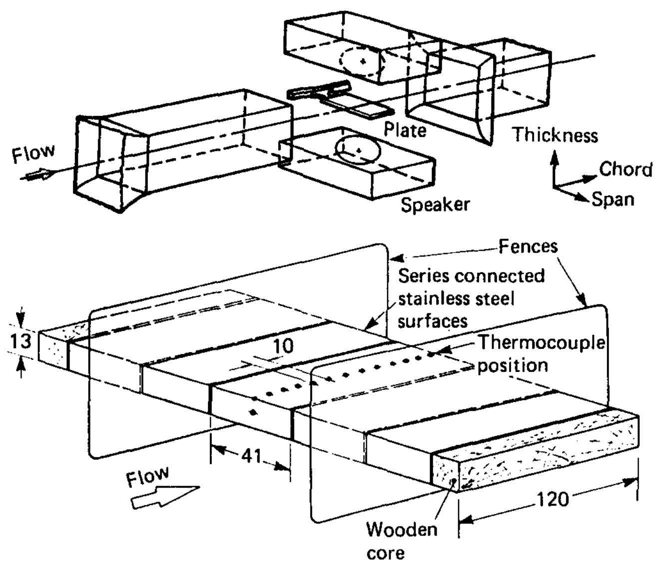

Fig 1 Schematic diagram of experimental equipment

Notation

A_f	Frontal area of plate for calculation of drag force
C_D	Drag coefficient, $F_0/(\frac{1}{2}\rho_\infty U_\infty^2 A_f)$
$C_{p\infty}$	Specific heat of air at upstream temperature
F_0	Drag force on plate
$\bar{h}$	Average heat transfer coefficient over the length of the plate
h_R	Heat transfer coefficient at reattachment
h_x	Heat transfer coefficient at distance x from the leading edge
k_∞	Conductivity of air at upstream temperature
L	Length of plate in flow direction and plate chord
Nu_R	Nusselt number at reattachment, based on reattachment length, $h_R x_R/k_\infty$
Nu_t	Nusselt number at distance x from leading edge, based on plate thickness, $h_x t/k_\infty$
Nu_x	Nusselt number at distance x from leading edge, $h_x x/k_\infty$
$\overline{Nu}$	Average Nusselt number over plate surface, $\bar{h}L/k_\infty$
Pr	Prandtl number, $C_{p\infty}\mu_\infty/k_\infty$
Re_R	Reynolds number based on reattachment length, $U_\infty x_R/\nu_\infty$
Re_t	Reynolds number based on plate thickness, $U_\infty t/\nu_\infty$
Re_x	Reynolds number based on distance x from leading edge, $U_\infty x/\nu_\infty$
$\overline{Re}$	Reynolds number based on plate length in flow direction, $U_\infty L/\nu_\infty$
t	Thickness of plate
U_∞	Free stream velocity
x	Distance from leading edge
x_R	Reattachment distance from leading edge
μ_∞	Dynamic viscosity of air at upstream temperature
ν_∞	Kinematic viscosity of air at upstream temperature
ρ_∞	Density of air at upstream temperature

to two outer sleeves which were rigidly attached to the tunnel structure. The floating inner 127 mm-wide section passed through the outer sleeves and connected to a support frame a drag balance situated below the lower speaker. Aerodynamically, the heat transfer plate and drag plate were similar.

The drag balance was constructed using a commercially available load cell connected in a load-sharing arrangement. A frame supported on four flexures effectively eliminated from measurement all forces other than that in the direction of the airflow. The natural frequency of the balance was designed to be low so that resonances would not be excited by the periodic vortex shedding from the plate under test when sound was applied. The measured resonant frequency of the assembly was approximately 8 Hz and all load cell voltage measurements were made using a filter set at 3 Hz, low pass.

Local convection 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 the small radiation losses. Drag forces were determined directly from the load cell voltage output, and the drag coefficient C_D was derived by dividing this force by the product of the dynamic pressure and the frontal area. Air velocities were determined by measuring the static pressure differences across the calibrated contraction upstream of the open jet section. Air properties were evaluated at the temperature upstream of the contraction. The reported velocities and any values derived from the measurements have not been corrected for errors due to the plate being inserted in a finite-width jet, which was less than 5% blockage. Estimates of the effects of blockage indicate a less than 1% effect on velocity in the worst case.

The ranges of variables considered were: approach velocities from 10 to 40 m s^{-1}, sound pressure levels of 100 dB to 122 dB (re 20 μPa), and sound frequencies from 400 to 1200 Hz in steps of 200 Hz. For all heat transfer tests, a constant electrical input gave a heat flux of about 1400 W m^{-2} and non-convective losses amounted to less than 1.5%. Measurements were taken when surface temperature measurements showed less than 0.05 K variation over two consecutive five-minute periods. After completion of the heat transfer tests, the drag plate was placed in position and, following calibration of the load cell, the drag force measurements were made. For each combination of velocity, sound pressure level and frequency, the no-load output of the cell was determined to establish the zero load voltage. The flow velocity was then set at the chosen nominal value and the cell output measured without sound. The sound field (which had been established previously) was then applied and the measurement repeated. A final cell output reading was taken after the sound was turned off, to check that the observed change in drag force was repeatable.

Results

Heat transfer

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

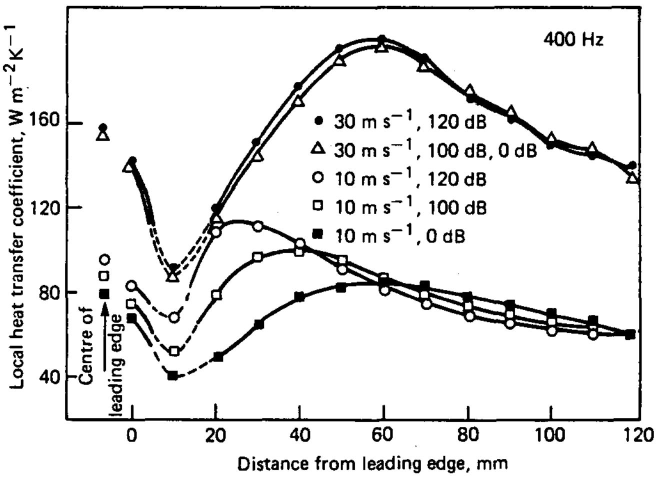

Fig 2 Local heat transfer coefficient as a function of velocity and sound pressure level at 400 Hz

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 of the temperature measuring points. The heat transfer coefficient then rises to a maximum whose value and position depend primarily on the free stream velocity and the sound pressure level.

The position of the maximum local heat transfer coefficient appeared to coincide with a position on the plate surface where a tuft probe did not show any particular tendency to point upstream or downstream. Small droplets of water introduced into this region were stationary on the plate surface. This position has commonly been termed the reattachment point, though flow visualization studies[1,15] have shown that the point on the surface at which the velocity along the plate is zero moves rapidly upstream and downstream with time. Ota and Kon[7] defined the reattachment point as a point of zero skin friction, its position having previously been determined in the mean by tuft probe examination[6,16]. They assumed from experimental observations that this reattachment point coincides with the point of maximum local heat transfer coefficient.

For this work, the mean position of reattachment is similarly defined as the position on the plate at which the local heat transfer coefficient will have a maximum whose value and location are derived from experimental measurements of surface temperatures. The position of the mean reattachment point from the leading edge was derived from the surface temperature measurements by curve fitting in the region of the minimum surface temperature (maximum local heat transfer coefficient) and differentiating to give the mean reattachment length and the maximum value for the local heat transfer coefficient.

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 other findings[6,7,9,17].

Increasing the sound intensity from 0 to 120 dB for a free stream velocity of about 10 m s^{-1} is seen to shift the mean reattachment point towards the leading edge and to increase the maximum heat transfer coefficient (Fig 2).

There is no significant movement of the position of minimum heat transfer coefficient, within the limits of spatial resolution. At 30 m s^{-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.

The dimensionless reattachment length is shown in Fig 3 as a function of both the sound pressure level in dB and the sound pressure in Pa rms for free stream velocities of 10, 15, 20, 30 and 40 m s^{-1} 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 m s^{-1} and above, there is no discernible effect of frequency. The reattachment length changes most rapidly for sound pressures from 0–100 dB (0–2 Pa rms) and is insensitive to sound pressures above about 100 dB (2 Pa rms), particularly at the higher free stream velocities.

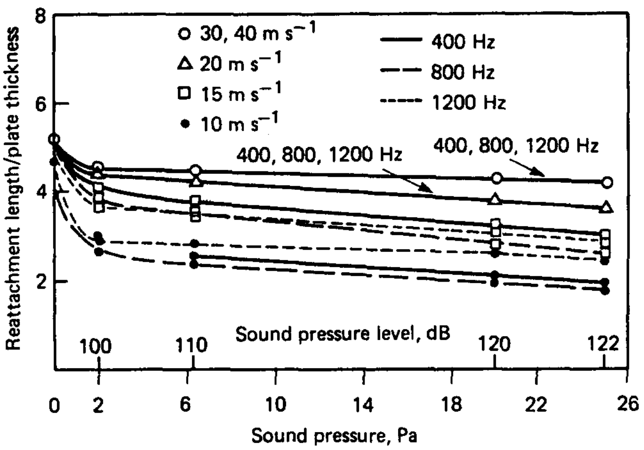

Fig 3 Dimensionless reattachment length as a function of sound pressure, frequency and air velocity

The correlation between the reattachment Nusselt number Nu_R and the Reynolds number Re_R, where both are based on the reattachment length, is shown in Fig 4, and a least squares fit to all the data in this study gives the following expression:

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

Also shown is the correlation found by Ota and Kon[7] based on results from experiments in which the reattachment length varied by changing the shape of the leading edge of the plate. There is obviously close agreement, with Ota and Kon's results having reattachment Nusselt numbers from 12% to 8% higher over a range of reattachment length Reynolds numbers from 10^4 to 10^5. The results of McCormick *et al*[8] from experiments in which the mean reattachment length of the separation bubble on a blunt flat plate varied with angle of attack also demonstrated a similar relationship between the Nusselt and Reynolds numbers based on the reattachment length, though the Nusselt numbers are from 42% to 47% higher over the range of Reynolds numbers from 10^4 to 10^5.

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 Fig 5 for a free stream velocity of 15 m s^{-1} with no sound and sound of 120 dB at 400 Hz. Also shown is the established correlation for forced convection heat transfer in a turbulent boundary layer over a flat plate. The significant influence of the separated flow on the Nusselt number in the region of reattachment can be seen. The Nusselt number for some distance upstream of reattachment is also above that which would prevail in the normal turbulent flow situation. The heat transfer downstream of reattachment more rapidly approaches the turbulent boundary layer case as the sound pressure level increases. Ota and Kon[7] noted that the elevated heat transfer coefficients resulting from separated and reattached flow persisted for a long distance downstream of the reattachment point and that the approach to the turbulent boundary layer case slowed as the slope of the nose angle increased up to a wedge angle of 180° (blunt leading edge).

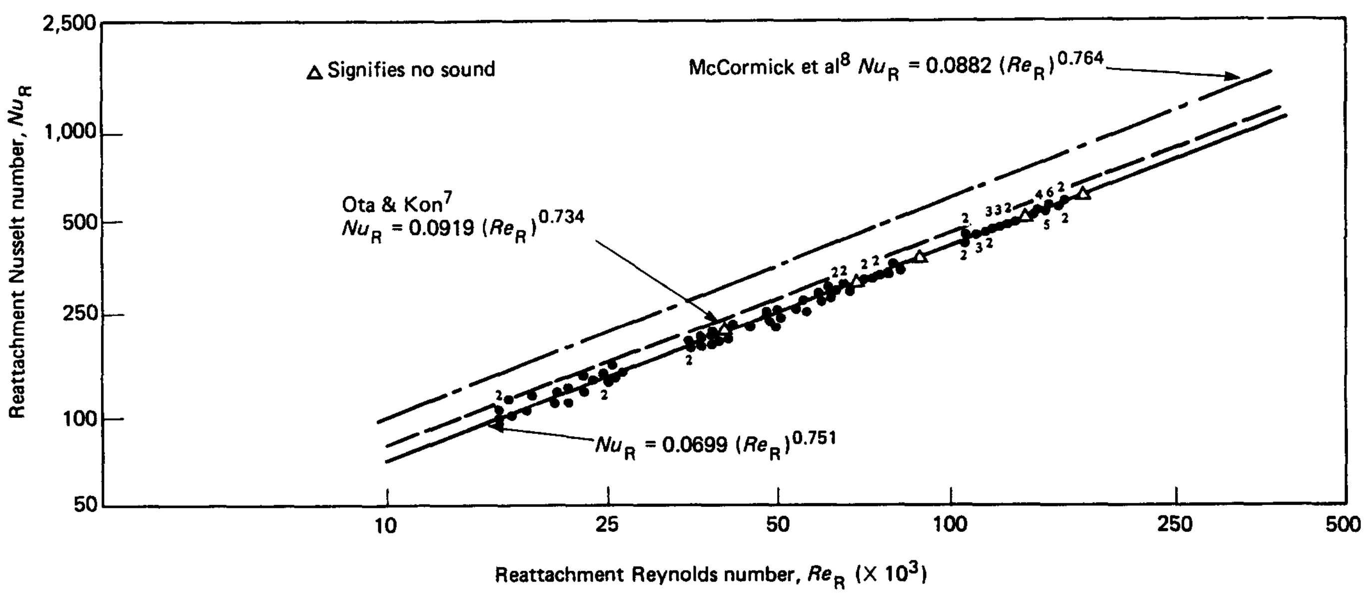

Fig. 4 Reattachment Nusselt number as a function of the reattachment Reynolds number

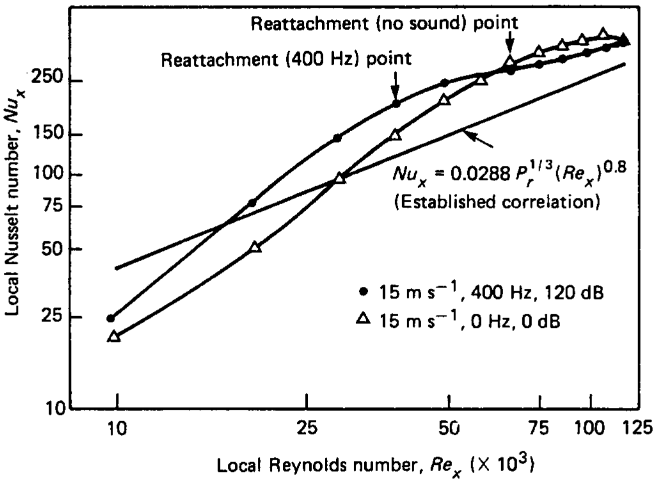

Fig 5 Local Nusselt number as a function of Reynolds number for a velocity of 15 m s^{-1} with no sound and sound of 120 dB at 400 Hz for increasing x

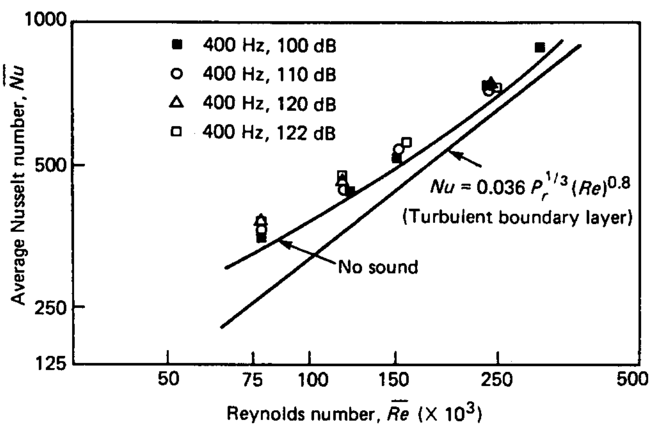

Fig 6 Average Nusselt number over plate as a function of Reynolds number based on plate length for no sound and sound of 400 Hz at sound pressure levels of 100, 110, 120 and 122 dB

The variation of the average Nusselt number Nu for the surface (based on the average heat transfer coefficient over the chord of the plate) with velocity and sound pressure level is shown in Fig 6 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 8×10^4 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 3×10^5, the average Nusselt number is about 7% greater than the turbulent value, rising to about 12% when the sound field is applied.

Drag

The effect of the asymmetric acoustic field is shown in Fig 7 where the percentage change in drag force relative to no sound is plotted as a function of free stream velocity and sound pressure levels for different frequencies. For clarity only the points at 10 and 40 m s^{-1} for a frequency of 600 Hz are shown. The figure shows a clear trend of the percentage change increasing with sound pressure level and decreasing velocity. At 100 dB there was little change detectable outside that due to experimental uncertainty (estimated to be $\pm 2\%$ change in drag force) even at a velocity of 10 m s^{-1} whereas changes in local heat transfer coefficients for the same conditions were clearly evident, as shown in Fig 2. Fig 7 also shows that, except for a frequency of 400 Hz at 10 m s^{-1} and sound pressure levels of 120 dB and above, frequency does not appear to have a significant effect on the drag force.

The drag coefficient C_D is shown as a function of the free stream velocity in Fig 8 for no sound and sound pressure levels of 110 dB and 122 dB. Without sound the drag coefficient is seen to increase in a linear fashion from a value of about 1.0 at 10 m s^{-1} to about 1.05 near 30 m s^{-1}. At about 40 m s^{-1} there is a departure from linearity which would require a velocity error of the order of -1 m s^{-1} at a nominal velocity of 40 m s^{-1} to be attributed to experimental error. It is estimated that the velocity measurements upstream of the model are better than $\pm 1\%$.

Though the drag coefficient increases with sound pressure level at low velocities, there is little difference evident above 20 m s^{-1}. For a sound pressure level of 122 dB the drag coefficient at 10 m s^{-1} is approximately 10% greater than that measured without sound and decreases in a linear manner with increasing velocity up to about 30 m s^{-1}. The rise at 40 m s^{-1} was found with all measurements with and without sound. On the assumption that the asymmetric sound field used in this investigation triggers the same flow mechanism as is evident with the flow of a turbulent air stream over a blunt flat plate, it could be expected that the effect of turbulence intensity on the drag coefficient measured by Jancauskas[13] would show a similar effect to increasing the sound pressure level. In the respective investigations, there is essentially no effect of turbulence intensity or sound pressure level for an Re_t of about 2×10^4.

Discussion

Heat transfer

The increase in the local heat transfer coefficient with sound pressure level shown in Fig 2 followed by a decrease (relative to lower sound pressure levels) some distance downstream of reattachment indicates the influence of patches of vorticity in the boundary layer along the plate. Parker and Welsh[1] noted these structures in their visualization studies and it is probable that they are dominant in generating the variation of local heat transfer coefficient with sound. The structures initially increase the local coefficient because of higher vortex-induced instantaneous velocities along the plate surface and the vortical motion bringing free stream fluid close to the surface near reattachment. Further downstream, the local coefficient decreases for higher sound pressure levels as a result of the structures' increasing in temperature because the bulk transport of hot fluid away from the surface and into the free stream is inhibited. The subsequent higher surface temperature leads to a decrease in the derived heat transfer coefficient.

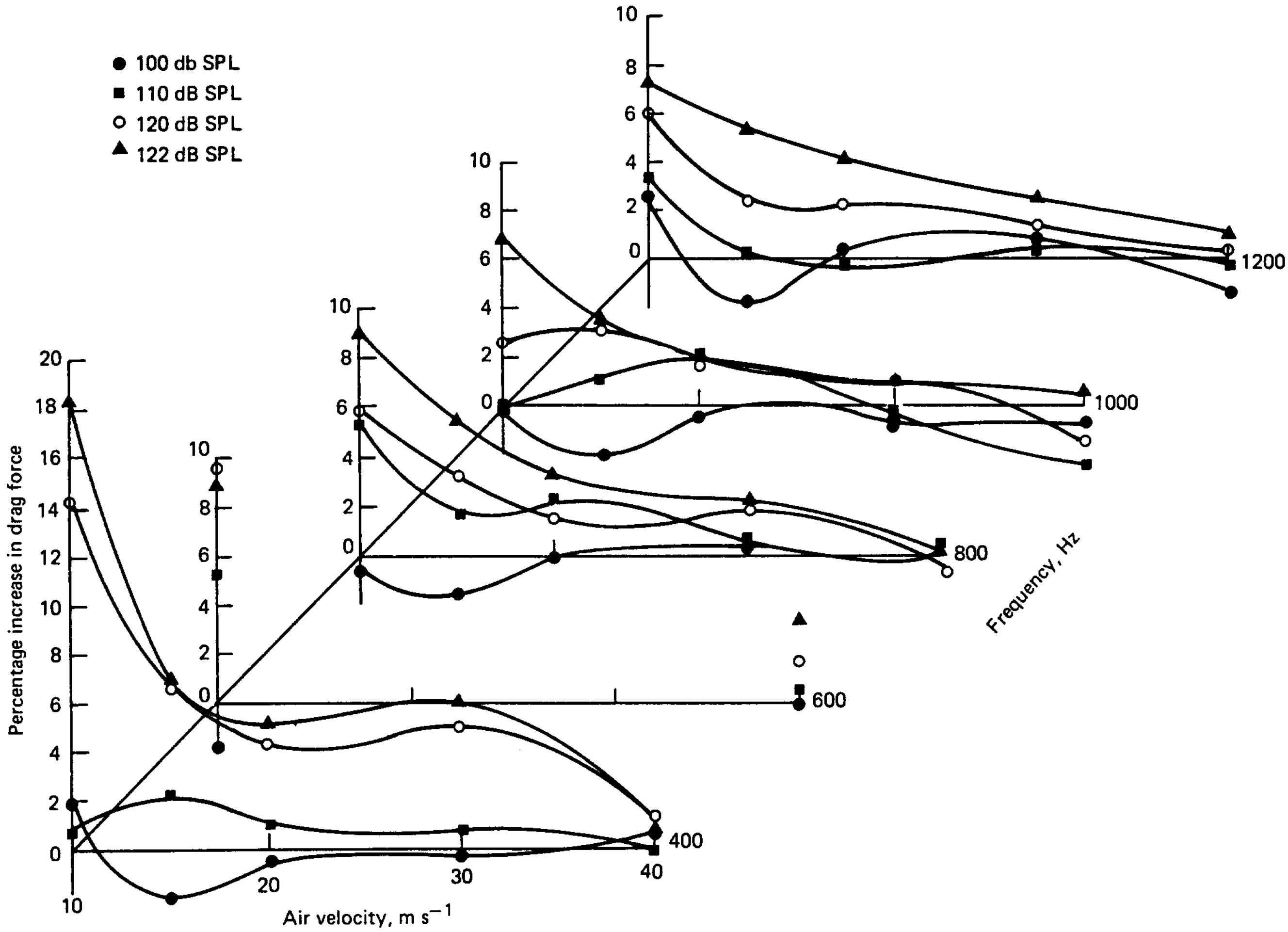

Fig 7 Percentage change in drag force on application of sound field as a function of free stream velocity, sound pressure level and frequency

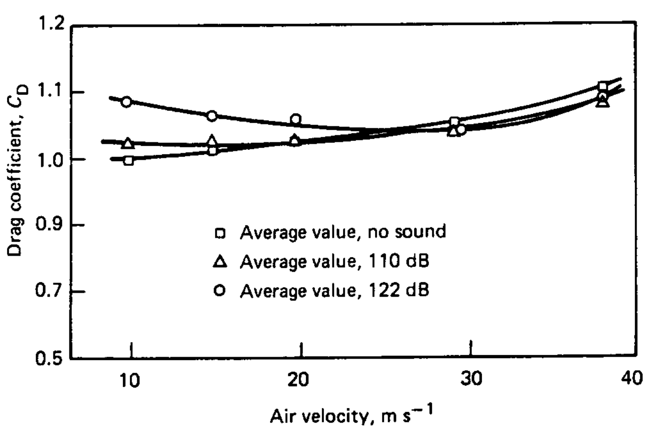

Fig 8 Drag coefficient as a function of free stream velocity and sound pressure level

A better understanding of the heat and fluid flow phenomena will result from observing the instantaneous velocity and temperature distributions in the fluid. As well, a numerical investigation has commenced to complement the experimental work, and initial results[18] are providing an understanding of the experimental phenomena reported here.

Ota and Kon[7] also showed a decrease in local heat transfer coefficient beyong reattachment with decreasing included angle of the nose of the plate (ie with reducing reattachment length), while a similar effect is shown by McCormick, Lessman & Test[8] with increased angle of attack of their experimental plate. All three methods of modifying the flow around the plate appear to be triggering the same mechanism that shortens the reattachment length of the separation bubble, increases the local heat transfer coefficient near reattachment and reduces it further downstream. The similarity at reattachment has been illustrated in Fig 4. Further evidence of this similarity is shown in Fig 9, where the local time average Nusselt numbers down the plate from this work and Ref 7 are compared. The data of Ref 7 are derived from Fig 2 of that paper, where results presented in graphical form at $Re_{t/2}$ values of 6800 and 5000 for a nose angle of 120° have been interpolated to an $Re_{t/2}$ of 6340 for direct comparison with experimental points measured at 120 dB sound pressure level (re 20 μPa) and 400 Hz sound frequency. In both cases the reattachment length, normalized to the plate thickness, was 3.2. The agreement at reattachment and downstream is evident, reinforcing the concept of a mechanism which can be triggered by a variety of disturbances to the flow. There is no reason to expect similar variations in local heat transfer coefficient prior to reattachment, as the flow in the separation bubble will be strongly determined by the geometry of the leading edge.

The three studies compared above were all for low longitudinal turbulence intensities in the approaching airstream. Kiya and Sasaki[15] showed experimentally that the length of the separation bubble reduces significantly

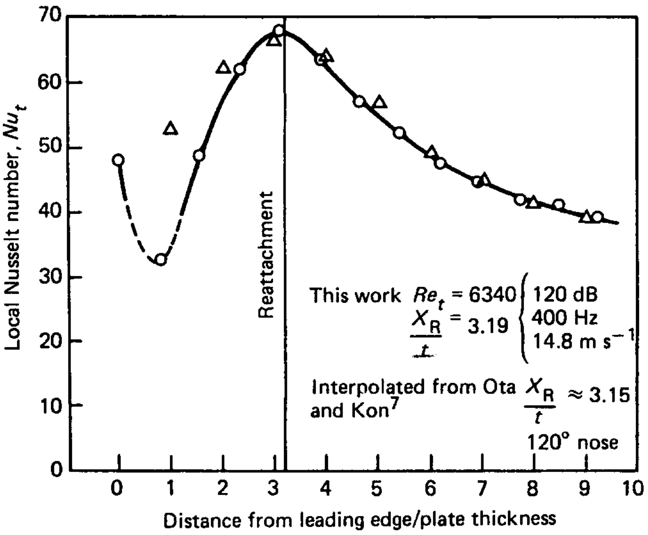

Fig 9 Comparison of local heat transfer coefficients for the same Re_t *and dimensionless reattachment lengths*

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 separation bubble length are similar. This suggests that the ratio of the acoustic particle velocity (which is proportional to the sound pressure level 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, the data does not correlate to reveal a simple relationship between reattachment length and the sound and flow variables.

The higher heat transfer coefficients at reattachment reported by McCormick, Lessman and Test[8] compared to those found by Ota and Kon[7] and the experimental results reported in this study have been attributed to the difference resulting from the use of a constant temperature surface rather than a constant heat flux surface (as was also used in this study). This difference is normally only apparent in laminar, unseparated flow which probably does not prevail for the flow conditions being studied. An experimental investigation of the instantaneous flows occurring and their influence on the heat transfer from the surface should assist in understanding the basic mechanisms occurring.

Drag

The measured total drag force is a combination of form drag due to a pressure difference between the leading and trailing edge and skin friction drag along the chord. It is estimated that the skin friction drag (based on developed turbulent flow) is less than 10% of the total and that, as a consequence, any changes in skin friction due to the effect of the sound field would not be significant. The changes in drag when sound is applied are due almost certainly to reductions in the mean pressure along the trailing edge, which were apparent in this study from exploratory measurements with a pressure probe. Because the time-averaged reattachment length varies with the application of a sound field, attempts were made to find some meaningful correlation between the reattachment length (deduced from Fig 3 for each combination of flow and sound variables) and the drag force. There appears to be no simple relationship.

The value of approximately 1.0 obtained for C_D in this work with $L/t = 9.23$ does not compare favourably with the value of $C_D = 1.4$ obtained by Jancauskas[13] for smooth flow at a similar Re_t with $L/t = 10.00$. The value of 1.4 is also considerably in excess of the value of 1.1 given in the draft code of the NAASRA Bridge Design Specification[19]. Jancauskas[20] has indicated that, in his test apparatus, for high chord to thickness ratios it was difficult to maintain accuracy and repeatability standards; measurements of drag forces were of lesser importance than those of lift and were accorded a lower priority in the design of his force balance. In the work reported here, some scatter was evident in the measured drag forces, particularly at low velocities when the total drag forces were of the order of 0.1 N. Repeated measurements at low velocities indicated that the scatter, resulting from the method of construction of the balance/load cell assembly, was essentially random and was unimportant above $20\,m\,s^{-1}$. Consequently, all drag results reported are the arithmetic means of a number of readings.

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 $20\,m\,s^{-1}$ for sound pressure levels up to 122 dB. For no sound, the reattachment length was not influenced by the free stream velocity.

At some point 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 instantaneous fluid mechanics and heat transfer downstream of reattachment, but the effect is believed to be due to ordered structures resulting from the sound field inhibiting the transfer of heat from the near surface into the mainstream.

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 tested. 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 8×10^4, and by about 12% at a Reynolds number of 3×10^5.

The drag coefficient for the flat plate was found to increase slightly with velocity in a close to linear fashion over the range from 0–40 m s^{-1}, with an average value of about 1.05. The effect of the sound field was to increase the drag force by about 10% at 10 m s^{-1} and 122 dB sound pressure level, with the percentage change decreasing at higher velocities and sound pressure levels. As with the time-averaged heat transfer results, sound frequency generally had little effect except at velocities below 20 m s^{-1} for a frequency of 400 Hz.

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