Effect of Acceleration on the Heat Transfer Coefficient on a Film Cooled Surface

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ABSTRACT

Results are presented of an experimental investigation into the influence of mainstream acceleration on the heat transfer coefficient downstream of injection through a row of 35° holes in a flat plate. A mass transfer analogue technique was used, with two uniform acceleration parameters, \( K = \frac{v(du/dx)}{u^2} \), of \( 1.9 \times 10^{-6} \) and \( 5.0 \times 10^{-6} \) in addition to the zero acceleration base-line case.

Two injectants, air and carbon dioxide, were employed to give coolant to mainstream density ratios of 1.0 and 1.52 respectively. The blowing rate varied from 0.5 to 2.0.

The heat transfer coefficient beneath the film reduced progressively as the acceleration increased, with maximum reductions from the zero acceleration datum case of about 27%. In the presence of acceleration, the heat transfer coefficient at a given blowing rate was dependent on the density ratio, an increase in the density ratio leading to a decrease in the heat transfer coefficient. An empirical correlation of the data over most of the range of densities and blowing rates of the experiments has been developed.

NOMENCLATURE

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INTRODUCTION

The high temperature environment of gas turbine nozzle vanes and rotor blades may necessitate the use of film cooling to protect the exposed surfaces. In film cooling, relatively cool air bled from the compressor is injected on to the blades surface via one or multiple rows of holes.

For heat transfer calculations, the cooling effect is customarily expressed in terms of a heat transfer coefficient, \( h_t \), defined by:

\[
h_t = \frac{q}{T_w - T_x}
\]

and a film cooling effectiveness, \( \eta_{aw} \), defined by:

\[
\eta_{aw} = \frac{T_w - T_{aw}}{T_w - T_x}
\]
where $q$, is the wall heat flux, $T_w$ and $T_{in}$ are the temperatures of the wall and adiabatic wall respectively, and $T_m$ and $T$ are the mainstream and coolant temperatures.

In gas turbine practice, large pressure and temperature gradients may be present over film cooled areas. An appreciation of their influence on the heat transfer coefficient under cooling films, $h_{in}$, is vital for heat flux calculations, and, hence, for proper cooling system design. The effect of mainstream pressure gradient in particular has received little attention.

Hartnett et al (1961) and Warren and Metzger (1972), both blowing via an angled flush slot, found that the effect of low acceleration was weak. In the latter study, an appreciable decrease in the heat transfer coefficient was observed at low blowing rates when the favourable pressure gradient was sufficiently strong for re-transition of the turbulent boundary layer to laminar state in the absence of injection. As the blowing rate increased towards unity, the depressed heat transfer coefficients increased toward their fully turbulent values.

Jabbari and Goldstein (1978), using a staggered double row geometry, found that the centreline and spanwise averaged heat transfer coefficients normalised by those without injection were not affected significantly by acceleration when the blowing rate was less than one. At higher blowing rates, a reduction of about 10% was found close to the injection point. This reduction extended further downstream as the blowing rate increased. The suppression of injection-induced turbulence by mainstream acceleration was suggested as a possible cause.

Liess (1975) gave the suppression of the development of streamwise vortices by the mainstream acceleration as the possible reason for the fall in the spanwise average heat transfer coefficients he found downstream of a single row of 35 deg inclined holes. Hay et al (1984) used an identical injection angle, and, additionally, normal injection. They reported large reductions in the heat transfer coefficient under the film when the blowing rates were low or the acceleration was strong.

By contrast, Kruse (1985) found acceleration effects to be weak for single row injection at 10°, 45°, and 90°. He also examined the effect of adverse pressure gradient, concluding that this too had only a weak effect on the heat transfer coefficient. This is in agreement with the results of Hay et al (1984) for a slightly stronger deceleration.

Thus, although it is generally agreed that acceleration reduces the heat transfer coefficient under a cooling film, there is conflicting evidence regarding the strength of the effect. Further, the effect of variation of the jet to mainstream density ratio appears not to have been considered in combination with mainstream acceleration.

In this paper, systematic work is presented on the effect of acceleration on the cooling film heat transfer coefficient for injection through a row of 35° holes. Density ratios of 1.0 and 1.52 have been used employing air and carbon dioxide injection with a mass transfer analogue technique.

**EXPERIMENTAL TECHNIQUE AND APPROACH**

The mass transfer technique employed uses a swollen polymer surface and laser holographic interferometry (Macleod and Todd, 1973). The technique provides high resolution results over the whole surface under study.

The test surface is coated with a silicone rubber polymer swollen to equilibrium in a swelling agent. The uniform concentration of the swelling agent over the surface simulates an isothermal wall condition. Exposure of the swollen coating to the film cooling flows results in evaporation of the swelling agent such that the recession in the polymer coating thickness is proportional to the local mass transfer coefficient (Macleod and Todd, 1973). The coating recession is measured by laser holographic interferometry which yields a fringe pattern from which the heat transfer coefficient is deduced. For a more comprehensive description of the technique see Hay et al (1982).

The heat transfer coefficient, $h$, measured by the present analogous mass transfer technique when the mass-transferring agent is absent from both the mainstream and coolant flows corresponds to $h_0$ (Ammari et al, 1989a).

**APPARATUS AND TEST CONDITIONS**

The experiments were conducted in a subsonic, low turbulence, open-circuit wind tunnel, Fig. 1. A description of the tunnel and its test section is given elsewhere (Ammari et al, 1989b). Contoured roofs were fixed to the top wall of the test section in order to produce the required uniform accelerations.

The injection geometry is shown in Fig. 1. Two gas injectants were used: air drawn from the same supply as the mainstream and carbon dioxide fed from pressurised bottles. The injectant was regulated, controlled and metered, then passed through a plenum chamber containing a straightener and gauge screens before entering the injection tubes.

Steady state, isothermal conditions prevailed during all tests. The experimental main parameters and operating conditions were:

- Injection hole diameter = 2.30mm
- Hole spacing to diameter ratio = 3.0
- Injection hole streamwise inclination = 35°
- Number of injection holes = 7
- Mainstream velocity at the injection location = 25 m/s, giving a Reynolds number, $Re_0 = 3.8 \times 10^5$ for all cases considered.
- The mainstream intensity of turbulence was 0.68%.
- The approaching boundary layer was fully-developed, two-dimensional and turbulent.
- In absence of acceleration the boundary layer displacement thickness to hole diameter ratio, $\delta/D$, at the injection location was 0.40.
- The flow within the injection tube exits was fully developed and turbulent during all tests. The maximum tube-to-tube variation of injected flow was less than one percent.
- Density ratio = 1.0 & 1.52
- Blowing rate = 0.5, 1.0, 1.5 & 2.0
- The variation of the mainstream velocity, $u_m$, normalized by the mainstream velocity at the point of
injection, \( u_0 \), and that of the pressure gradient parameter \( K \) are shown in Fig. 2 as a function of the dimensionless distance \( x/D \).

![Graph showing mainstream velocity and acceleration parameter variations](image)

The dimensionless distances covered by effectively constant acceleration were as follows:

- **case (A)**, \( K = 0.0 \), \(-5 \leq x/D \leq 60\),
- **case (B)**, \( K = 1.9 \times 10^{-6} \), \(-5 \leq x/D \leq 50\) and,
- **case (C)**, \( K = 5.0 \times 10^{-6} \), \(-5 \leq x/D \leq 30\).

For case (A) the flat test section roof was flat. Although the acceleration of \( K=5 \times 10^{-6} \) produced considerable thinning of the boundary layer and thickening of the viscous sublayer, particularly far downstream, the distance subjected to strong acceleration was not sufficient for flow relaminarisation (Ammari, 1989).

It has been shown that, for zero pressure gradient in the presence of injection, a large change in the approach boundary layer condition (from thick, turbulent to thin, transitional) produces no measurable change in the cooling film heat transfer coefficient (Hay et al, 1984). It would seem logical to assume that the heat transfer coefficient under films injected into regions with non-zero pressure gradients are similarly insensitive to approach boundary layer conditions. In the current work, therefore, no attempt was made to keep the approach boundary layer thickness constant when the acceleration was varied.

Applicability of the present technique for the measurement of heat transfer coefficient without injection as well as with foreign gas injection has been validated by Ammari et al (1989b).

Uncertainty analysis was carried out according to the method of Kline and McClintock (1953). The uncertainty on the heat transfer coefficient ratio with and without injection, \( h/h_0 \), was estimated to be ±4.0% in the near field \((x/D<10)\) and ±5.0% in the far field \((x/D>10)\). The uncertainties associated with the laterally averaged heat transfer coefficient, \( h/L \), were rather larger, ±7.9% and ±9.4% in the near and far fields respectively. Uncertainty on the absolute mass transfer coefficient was ±6.7%, so that the uncertainties on the ratios \( h_p/b \) and \( h_m/b \) in the presence of favourable pressure gradients were even larger at ±9.4% and ±8.2% respectively in the near field, and ±13.4% and ±12.4% respectively in the far field, since the analysis was dependent on division of two averaged absolute heat transfer coefficient values. Bias domination of the error of the absolute coefficients would result in a much reduced error in the ratio. However, no clear evidence of a bias has been found so far.

**RESULTS AND DISCUSSION**

The results are presented as ratios of local and laterally averaged heat transfer coefficients with and without injection, and also as the ratio of laterally averaged heat (mass) transfer coefficient under the film in the presence of the favourable pressure gradient to that with zero pressure gradient conditions at the same location and blowing rate. In this way, both the effect of injection on the boundary layer, and the factor by which the heat transfer coefficient are altered by the imposition of a favourable pressure gradient are quantified.

**Mainstream Acceleration**

The interference fringes mapping constant mass transfer contours, Fig. 3, provide a clear picture of the variation in the structure of jet-mainstream mixing due to acceleration. The three interferograms shown are all for a blowing rate of unity at three different pressure gradients; zero, (A), moderate favourable, (B), and strong favourable,

![Interference fringes mapping constant mass transfer contours](image)

Grid Spacing = 5D

![Fig 3. Interference fringes giving contours of constant mass (heat) transfer coefficient for air injection at M=1](image)
The tests were run for equal times (12 minutes) and at temperatures of 27°-29°C, so that the fringe patterns provide a direct comparison of heat transfer coefficients.

The figure shows that the lateral spread of the jets downstream of the holes is reduced by the acceleration, most notably in case (C). Close to the injection site, the jet flows seem to be more compact and therefore more independent of each other. This behaviour has also been observed by Foster (1976) for 90° injection with s/D=3. He measured jet concentrations at x/D=4.25 and z/D=0.0-1.5 above a film cooled wall at zero and strong favourable (K=8.5x10^4) pressure gradients. A reduction in the lateral spread of jets issuing from staggered rows of holes aligned at 45° with s/D=8 was also reported by Launder and York (1974) for an acceleration parameter of 2.0x10^6.

The pattern of the mass transfer contours is generally similar at all accelerations. The peak in the local mass (heat) transfer coefficient corresponding to the maximum coating shrinkage downstream of the hole centreline happens at the same position, about x/D=2.4. Thus, separation may have occurred even at K=5.0x10^4, with reattachment at almost a fixed location.

Similar behaviour to that in Fig. 3 was seen at the other blowing rates used in this study.

To demonstrate the response of the injectant jets to the acceleration, the centreline turbulence intensity (longitudinal velocity fluctuations only) and mean velocity profiles of air injection at x/D=5 with and without acceleration of K=5x10^4 are plotted in Fig. 4. The most striking acceleration effect is the amount by which the injection introduced turbulence is reduced. The effect of acceleration on the turbulence intensities is larger than on the mean velocities. The peaks appearing in the turbulence intensity profiles correspond to the edges of the jet core where intensive jet-mainstream mixing takes place.

As M increases, jet penetration and turbulence intensity increase. The favourable pressure gradient reduces turbulence intensities, and gives slightly lower jet trajectories. This latter effect may arise at least in part from the thinner approaching boundary layer, with its reduced momentum deficit.

The reduction in turbulence intensity in the non-injected boundary layer is accompanied by a progressive drop in heat transfer coefficient, as seen in Figure 5. These results are in agreement with the findings of Back et al (1970) who reported heat transfer rates considerably below expected magnitudes for turbulent flow when K was above 2.3x10^4.

Injection gives rise to increased heat transfer coefficients, see Figure 6. The accelerated flow cases follow a generally similar pattern to that for zero pressure gradient. After the initial peak associated with injection, the heat transfer coefficient ratio falls to a value dependent upon the blowing rate. Higher blowing gives increased heat transfer coefficients.

Under moderate acceleration, the suppression of turbulence by the pressure gradient results in the heat transfer coefficient ratio falling steeply at the end of the constant acceleration region, and it seems plausible that they too would approach non-injected levels given sufficient development length. The presentation of heat transfer coefficient data as a ratio to
non-injected levels, as here, gives a picture of the effect of injection on the boundary layer, but the comparison of values at different pressure gradients is not useful because of their dependence on the initial boundary layer. It has been noted earlier that the heat transfer coefficient under the film is relatively insensitive to this, so to gain a clearer impression of the effect of the pressure gradients on the film heat transfer coefficients, the data is presented also as a ratio of the spanwise averaged value under a pressure gradient to that at the same location with no pressure gradient, see Figures 7 and 8.

As the patterns of interference fringes of equi-recession at zero and favourable pressure gradient conditions do not differ greatly (see Fig. 3), the trends of the ratios of local and lateral average heat transfer coefficients downstream of injection were found to be generally similar.

In the presence of strong favourable pressure gradient (K=5.0x10^-6), a more definite variation of the reduced cooling film heat transfer coefficient with blowing rate, M, is observed. Fig. 8. In general, the strong mainstream acceleration appears to lower significantly the heat transfer coefficient all the way downstream particularly at lower M's. This behaviour was also observed by Hay et al (1984). The lateral average heat transfer coefficient is now reduced by about 20% and falls further, by 27%, for low blowing, at locations further downstream, before commencing a slight recovery. At higher blowing rates, \( h_{\text{rej}} \) ranges between 80% of the value for the zero pressure gradient close to the injection point to 86% far downstream.

An increase in \( h_{\text{rej}} / h \) with M may be expected since at \( K=5.0x10^{-6} \) the boundary layer is very thin, \( S/D=0.6 \) at \( x=D/5 \), and the emerging jets readily penetrate it and encounter the high mainstream velocity.

The jet trajectory at a given M therefore tends to be lower for this case than for the zero or moderate pressure gradient cases. The thinner boundary layer also mixes less with the jets, leaving tighter structures. The heat transfer coefficients will therefore tend to reflect the jet behaviour more directly, and hence will respond to factors, such as M, which influence it. It should be noted, however, that although the differences in the values of \( h_{\text{rej}} / h \) resulting from varying M now reach as much as 10%, this is still within the uncertainties associated with the curves themselves.

To examine the correlation of the heat transfer coefficient with acceleration parameter, the average coefficients at the various pressure gradients, each normalized by that at zero pressure gradient, have been plotted against K for a range of fixed downstream positions in Figure 9. A roughly linear variation with K is seen, with only a weak, and inconsistent dependence upon M. Dispersion from the fitted line is small, within about ±7%, at all downstream positions.

Acceleration and Density Ratio

The tests with \( \rho_{h}/\rho_{f}=1.52 \) at \( K=5.0x10^{-6} \) showed the same general trends as those at \( K=0.0 \). Figure 10. The laterally averaged ratio \( h_{\text{rej}}/h_{\text{rej}} \) for \( M=1.0 \) increases significantly with M in the vicinity of the holes, and decays monotonically with \( x/D \). Now, however, \( M=0.5 \) yields a heat

![Fig. 7 Ratio of the laterally averaged heat transfer coefficient under a cooling film subjected to moderate acceleration to that for zero acceleration](image-url-7)

![Fig. 8 Ratio of the laterally averaged heat transfer coefficient under a cooling film subjected to strong acceleration to that for zero acceleration](image-url-8)

![Fig. 9 Correlation of the laterally averaged heat transfer coefficient with acceleration parameter](image-url-9)
transfer coefficient for the region $x/D > 5$ which is well in excess of those at higher blowing rates. Closer inspection of the zero pressure gradient curves in Figure 10 shows that the $M=0.5$ curve lies above that for $M=1$, over a short distance. A further test at $M=0.4$ was conducted under strong pressure gradient conditions, and this produced lower values than for $M=0.5$.

This behaviour is consistent with the occurrence of jet lift off at a blowing rate slightly greater than 0.5, corresponding to a momentum flux ratio, I, of 0.16. This is in fairly good agreement with the approximate limit of 0.1 given by Forth and Jones (1986) who recognised the need to develop separate correlations for predominantly attached and predominantly separated film cooling flows. These they identify as weak and strong injection regimes. It is evident that the bulk of the present work has been conducted with strong injection, with the single exception of the 0.5 blowing rate, high density ratio case, where reattachment occurs within the first 5 diameters.

The attached jets mix less with the mainstream, giving higher velocities close to the wall and, hence, increased heat transfer coefficients. The effect appears much more pronounced under strong acceleration than under zero pressure gradient conditions in Figure 10 partly because of normalisation by the non-injected heat transfer coefficients. Because the normalising factor is very low for the strong acceleration, high density ratio case, where reattachment occurs within the first 5 diameters.

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To clarify the effect of the pressure gradient on the film, the heat transfer coefficients normalised by their corresponding zero pressure gradient values, $h_{SF}/h_0$, are given as a function of $x/D$ with $M$ as parameter in Fig. 11. The curves for $1.0 \leq M \leq 2.0$ with CO$_2$ injection have the same form as those with air injection (Fig. 8), but are less sensitive to blowing parameter. Reductions in heat transfer coefficient for most downstream distances are about the same as for the two lowest air-injection blowing rates, but are rather higher close to the injection point at around 25%.

The most striking feature in Figure 11 is the difference in behaviour at the lowest blowing rate. Although the reduction in heat transfer coefficient close to the injection point is the same as for other blowing rates, this is not sustained. The heat transfer coefficient climbs progressively towards its zero pressure gradient level.

The influence of varying the density ratio from 1.0 to 1.52 at constant acceleration $K=5.0 \times 10^4$ on the heat transfer coefficient is shown in Fig. 12. The data are presented as lateral distributions of the local heat transfer coefficient for $M$ ranging from 0.5 to 2.0 at $x/D=3$, and $x/D=25$.

At $x/D=3$, and for $0.5 \leq M \leq 2.0$, a substantial decrease in the heat transfer coefficient ratio $h_{SF}/h_0$ of around 20% occurs when $\rho_2/\rho_0$ is increased by 52%. As stated in (Amnari et al., 1989a) for $K=0$, this behaviour is due to the denser injectant gas having a lower momentum at a fixed value of the blowing rate.
At x/D=25, the difference between $h_{w}/h_{0}$ at high and low density ratios is a maximum at $M=2$, and is near zero at $M=1$. For the higher blowing rates, the lower density ratio gives the higher heat transfer coefficient.

For $M=0.5$, an increase in density ratio from 1 to 1.52 is accompanied by a change in injection regime from strong to weak, as I decreases from 0.25 to 0.16. An increase in $h_{w}/h_{0}$ results from this change of flow regime. Similar, although smaller, increase was observed at $K=0.0$ (Ammari et al., 1989a). Recently, measurements of turbulence intensity at density ratios of 1.0 and 2.0 have been reported by Pietrzyk et al. (1989). Using an injection geometry identical to that used here, and a blowing rate of 0.5, they found that the turbulence intensity for unity density ratio was initially slightly the higher, but decayed quite rapidly with distance. The intensity for the higher density ratio fell only slowly. Although these measurements were made at zero pressure gradient, it seems likely that the same effect would occur under acceleration, and that the sustained high heat transfer coefficients seen at high density ratio and low blowing rate reflect a similarly sustained high turbulence intensity.

Close to a hole, a peak in the heat transfer coefficient for $M=0.5$ is observed at about $z/D=0.5$ at both density ratios. This is characteristic of low trajectory jets at zero pressure gradient conditions (Eriksen and Goldstein, 1974), where the centreline value of the heat transfer coefficient is lower than the value near the edge of the jet. As $M$ was increased the peak moved to the centreline and remained there.

Far downstream from a hole, the relatively high values of $h_{w}$ at the edges of a jet for $M=0.5$ at both density ratios, moved to the mid-position between the holes, $z/D=1.5$, as the blowing rate increased. This effect is due to jet spreading, interaction with adjacent jets, and the induced streamwise vortices.

The results are seen to be consistent with those found at zero mainstream pressure gradient (Ammari et al., 1989a) although the strong mainstream acceleration seems to enhance the influence of density ratio.

The effect of acceleration of $K=5.0 \times 10^{4}$ on the heat transfer coefficient at density ratios above unity is shown to differ only slightly in manner and magnitude to the effect at density ratio of one. An acceleration of $1.9 \times 10^{4}$ would, therefore, be expected to conform to the same pattern.

**Correlating Parameters**

It has been shown by Ammari et al. (1989a) that, at zero mainstream acceleration, the heat transfer data, including those with a density ratio of 1.52, correlated reasonably well with the velocity ratio parameter, $(x/D)(u_{j}/u_{w})^{0.40}$, in the strong injection regime.

Since most of the present heat transfer data lie in the strong injection regime and, the general behaviour of the cooling film heat transfer coefficient under favourable and zero pressure gradients is similar (see Figs. 6 and 10), it seems logical that the pressure gradient data should correlate with the zero pressure gradient correlating parameter, $(x/D)(u_{j}/u_{w})^{0.40}$. This is clearly shown to be so in Fig. 13, where a reasonable collapse of the pressure gradient heat transfer data is achieved.

An attempt to collapse all the experimental data excluding those at $u_{j}/u_{w}$ of 2 is shown in Fig. 14. The correlation incorporates the scaling parameter, $(x/D)(u_{j}/u_{w})^{0.40}$, and the linear relationship derived at unity density ratio to describe the effect of acceleration. The scatter, however, is seen to be large particularly for the high density ratio in presence of acceleration.

**Concluding Comments**

The present results support earlier conclusions that the effect of accelerations of moderate strength is weak, with around 10% reduction in heat transfer coefficient being recorded. Under strong acceleration, up to 25% reduction may occur, but the magnitude is more dependent on the blowing rate. The heat transfer coefficient has also been shown to be related to the turbulence intensity within the film.
The existence of weak and strong injection regimes has again been demonstrated. Although the effect of density ratio variation at a fixed blowing rate is generally not great, it has a key role in determining the weak-strong injection regime transition as this is momentum ratio dependent. The precise value at which transition occurs is likely to depend on details of injection geometry and velocity distribution, and may contribute to a lack of close consensus regarding acceleration effects.

CONCLUSIONS

1. Mainstream acceleration suppresses injection induced turbulence, and hence reduces the heat transfer coefficient.

At unity density ratio, the overall average reduction in the averaged coefficients, $h$, was about 8% under moderate acceleration, and fell from about 25 to 20% under strong acceleration as the blowing rate increased.

At a fixed blowing rate, the spanwise average coefficients normalized by the corresponding zero acceleration values, $h/(h)^0$, decrease almost linearly as the acceleration parameter, $K$, increases.

Blowing rate had a negligible effect on the heat transfer coefficients ratio at the lower acceleration. At the higher acceleration, increased injection weakened the effect of the acceleration on the coefficients ratio.

2. When the injectant to mainstream density ratio was 1.52, the imposition of a strong mainstream acceleration ($K=5\times10^{-4}$) had a similar effect on the film heat transfer coefficients as for unity density ratio, at least where the influence of $M$ was quite weak ($M<1.5$). A substantial overall reduction in $h/(h)^0$, of about 27% was present for $M>0.5$.

3. The effect on the heat transfer coefficient of raising the density ratio from 1.0 to 1.52 under strong acceleration was also similar to that at zero pressure gradient. The decrease in the coefficients reached 20% at some downstream positions for the large blowing rates.

4. Empirical evidence shows the heat transfer coefficient data in the presence of acceleration and with a density ratio of 1.52 to scale reasonably well with $(x/D)(u_0u_Y)\delta_0^{1/4}$, the data correlating parameter for zero acceleration. An initial attempt at an overall correlation, to include effects of both acceleration and density ratio variation, gave:

$$\frac{h}{h^0} = [1.0 -0.04(Kx10^{-4})][1.025 + 0.35 \exp{-0.15(x/D)(u_0u_Y)\delta_0^{1/4}}]$$

The scatter becomes large for the data at the higher density ratio in the presence of acceleration.

REFERENCES


