An Experimental Determination of Heat Transfer near the leading Edge of a film-cooled Gas Turbine Blade

A. Mirhosseini and H. Barrow†

This paper reports an experimental procedure for the determination of the local heat transfer coefficient in the vicinity of the leading edge of a film-cooled gas turbine blade. By invoking the heat-mass transfer analogy, and measuring the sublimation rate of naphthalene, the influence of film coolant ejection on the magnitude of the local transport coefficients is determined. A novel apparatus and experimental technique have been designed to eliminate the need to know the physical properties of the naphthalene. Results of experiments using a 'relative mass transfer method' for a blowing rate (injection velocity to mainstream velocity ratio) from 0·2 to 1·0 and a mainstream Reynolds number of $3{\cdot}48 \times 10^4$ are presented and compared with previous heat transfer data.

NOTATION

c_p	specific heat at constant pressure
c	concentration of sublimating material
D	diameter of cylinder
d	width of slot
h	local heat or mass transfer coefficient
$M\ (= u_s/u_\infty)$	blowing parameter
$\dot{m}$	mass transfer rate
ν	kinematic viscosity
$Re\ (= u_\infty D/\nu)$	Reynolds number
ρ	fluid density
$St\ (= h/c_p\rho u_\infty)$	Stanton number
Δt	change in thickness of sublimating material
u	velocity
x	distance from slot around cylinder surface

Subscripts

B	blown
UB	unblown
w	wall
s	slot
∞	mainstream

INTRODUCTION

The advent of the gas turbine and the rocket engine has led to the need for the efficient cooling of surfaces which are exposed to high temperature combustion gases. In this connection, conventional convection cooling methods are often inadequate and resort must be made to other techniques which include the now familiar 'film cooling' and 'transpiration cooling'. In these cases coolant is introduced through holes, slots, or porous surfaces on to the surface which is to be protected from the high temperature gas, with a view to maintaining the temperature of the wall within prescribed limits. Considerable effort has been made to understand the flow and heat transfer mechanisms involved in these processes, and a good account of film cooling in particular has been given by Goldstein (**1**).

Two parameters are of special interest with regard to the prediction of heat transfer in film cooling. These are the adiabatic wall temperature and the heat transfer coefficient. Evidently, most attention has been given to the prediction of the adiabatic wall temperature through the so-called effectiveness, with less effort directed towards the influence of the coolant ejection on the heat transfer coefficient. Most conveniently, the film cooling heat transfer coefficient may be assumed to be the same as that without film cooling. However, the injection of coolant into a flow adjacent to a surface may have a significant influence on the flow pattern there and hence on the heat transfer coefficient. It is with this particular problem that the present work is concerned.

In the experimental determination of local heat transfer rate, advantage may be taken of the heat–mass transfer analogy when a mass transfer experiment is more simple to effect. The essentials of the heat–mass transfer analogy are reported in the standard texts. It suffices here to state that if the nondimensional heat transfer coefficient (or Nusselt number) is a function of the Reynolds number and the Prandtl number, then the nondimensional mass transfer coefficient (or Sherwood number) is the same function of the Reynolds and the Schmidt number. It is essential to point out that the boundary conditions (and of course the geometry), must be the same. For example, an isothermal boundary condition in heat transfer may be simulated by a uniform wall concentration boundary condition in mass transfer. This latter condition may be achieved by the sublimation of a volatile material such as naphthalene, which has been used extensively since its introduction by Frössling (**2**), as early as 1938. The naphthalene mass transfer surface may be cast in a mould, cast on a surface and machined, or deposited as crystals on a surface in a sublimation chamber. The local mass transfer may then be determined by measuring the change in thickness, provided that the density of the deposited naphthalene is known. Alternatively, the naphthalene may be cast or deposited on detachable elements, in which case, weighing on a micro-balance affords a method of determining the mass transfer. An excellent method of depositing the

† Department of Mechanical Engineering, University of Liverpool, UK.

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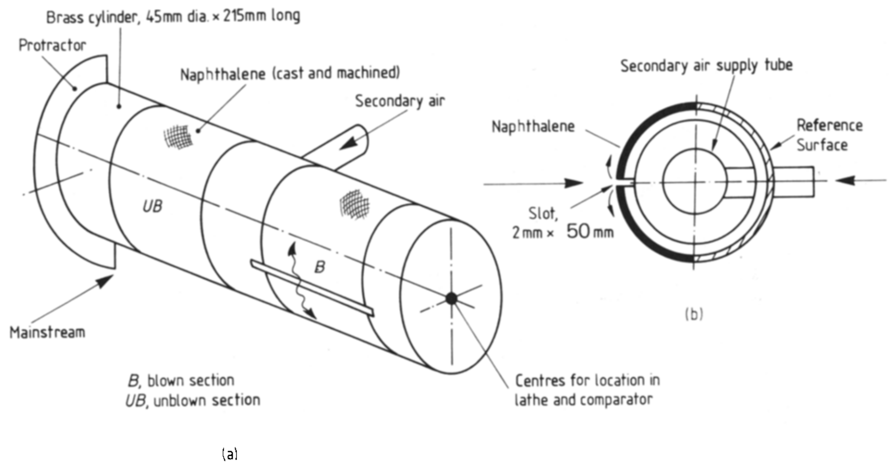

Fig. 1. Details of the model cylinder for the investigation of mass transfer with and without blowing. (a) Model cylinder. (b) Section in way of slot

volatile material on a surface is to use a dry-spraying method as described by Lee (**3**), in his study on spheres.

For the present purposes, heat transfer in film cooling is measured using mass transfer measurements from a cast and machined naphthalene surface as described in the following section. The local mass transfer rate is determined from the change of local thickness in a given period of time of sublimation.

With regard to the evaluation of the mass transfer coefficient (and hence the prediction of the heat transfer coefficient) for an immersed surface, the appropriate equation is

$$h = \frac{\dot{m}}{c_w} \tag{1}$$

when it will be observed that in addition to the density of naphthalene, it is necessary to know the wall concentration, c_w. Both the density and the vapour pressure of naphthalene (from which c_w may be evaluated) are given by Christian and Kezios (**4**), but the use of such data and in fact other pertinent properties are eliminated by the procedure outlined in the next section.

Recalling that it is the change in the heat transfer brought about by the film cooling which is required, the determination of absolute values of the transport coefficients is unnecessary. How this is effected in the laboratory is now described.

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows the model used to determine the influence of film cooling near the leading edge of a gas turbine blade. A circular cylinder in cross flow was chosen since the flow near the forward stagnation point simulates very closely the flow over the rounded leading edge of the blade. In the design it was necessary to provide for film cooling and for the measurement of the effect of the coolant flow on the local heat transfer coefficient. As described in the last section, the use of the properties of the sublimating material may be eliminated and this was effected by conducting two experiments simultaneously as shown in Fig. 1(a). A radial coolant slot which extended over part of the length of the cylinder was machined in order that measurements with and without blowing could be taken at the same time and under identical external flow conditions and temperature. Furthermore, casting of the naphthalene in shallow grooves on the two sections of the cylinder in the same process ensured uniformity of the material with regard to structure and density. The naphthalene surfaces in the blown and unblown regions were machined in a lathe, the grooves in the rear halves of the sections being filled with fibre glass fillers to provide a reference surface for the measurements of changes in the thicknesses of naphthalene as shown in Fig. 1(b). The diameters of the cylinder in the blown (B) and unblown (UB) sections were measured in a 'Matrix floating carriage diameter measuring machine' having a micrometer head with a minimum division of 0·000 254 mm and a fiducial indicator as shown in Fig. 2. Accordingly, the profiles of the naphthalene castings could be measured before and after operation for a known time in steady flow in a wind tunnel.

Figures 3 and 4 are photographs of the cylinder installed in position in the wind tunnel during test. For a given mainstream velocity of 11 m/s, corresponding to a cylinder Reynolds number of $3{\cdot}48 \times 10^4$, the experiment was conducted for various values of slot velocity/mainstream velocity ratio. In each test, the profile of the naphthalene coating was measured in the blown (B) and unblown (UB) regions before and after the experiment. Since in both regions the density and the surface concentrations are the same, the changes in thickness (or diameter) at any given angular location are proportional

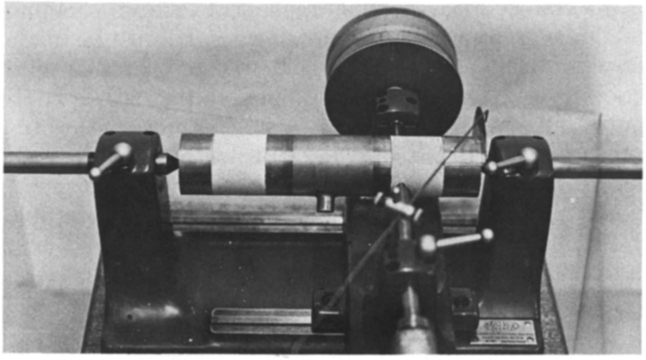

Fig. 2. Measurement of the local thicknesses of the naphthalene sections in the 'Matrix floating carriage diameter measuring machine'

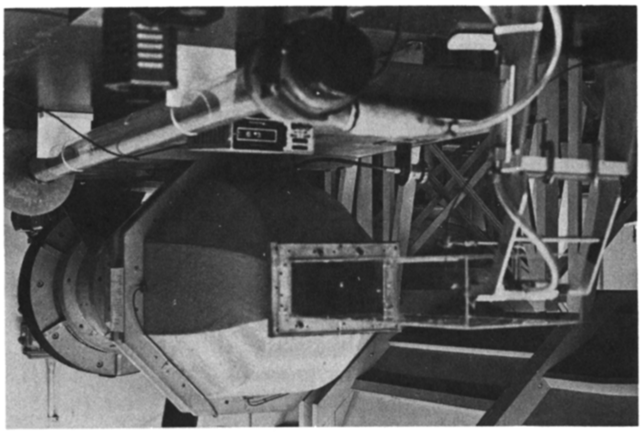

Fig. 3. Arrangement of the apparatus showing the cylinder located near the wind tunnel outlet, and the secondary air supply

to the mass (heat) transfer coefficients in the two regions. That is

$$\frac{h_B}{h_{UB}} = \frac{\Delta t_B}{\Delta t_{UB}} \tag{2}$$

In this way, the change in heat transfer coefficient as a consequence of film cooling could readily be determined. The absolute values of the coefficients near the stagnation point of a cylinder in cross flow are known accurately, in which case those with blowing may be calculated if required.

In summary, the advantages of the present procedure are as follows.

(1) The experiments for the 'unblown' and 'blown' situations are conducted under the same conditions with regard to temperature, flow velocity and geometry, and turbulence level in the mainstream.
(2) Problems concerned with the uncertainty of the data on the properties of the sublimating material are circumvented.

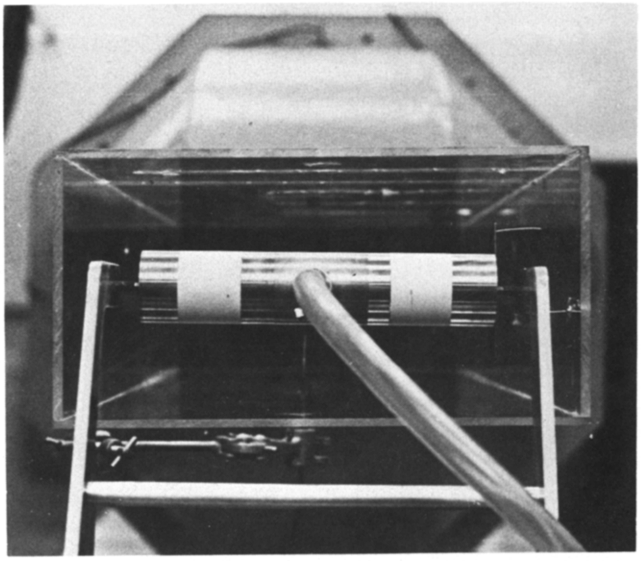

Fig. 4. Rear view of the model cylinder showing the measurement reference surfaces of the two mass transfer sections, the secondary air inlet, and the protractor for determining angular positions around the cylinder

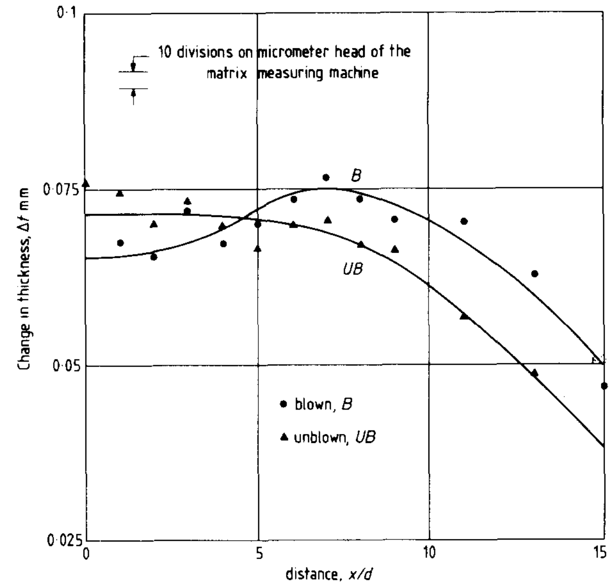

Fig. 5. Sublimation mass transfers with and without blowing after 2 hr ($M = 0{\cdot}2$, $Re = 3{\cdot}48 \times 10^4$)

(3) Only a single measurement of thickness (which, for example, may be accurate to ± 1 per cent for a time of experiment of about 2 hr), is required.
(4) The error introduced by heat loss in a heat transfer experiment is eliminated.

The results and observations in the mass transfer experiment are presented in the next section and a comparison is made with some earlier heat transfer results reported by Goldstein (**1**).

EXPERIMENTAL RESULTS AND DISCUSSION

Local mass transfers from the cylinder with and without blowing are shown in Figs. 5, 6, and 7 in which the values of the pertinent test variables are included. In these figures the change of local thickness, Δt, has been plotted versus the nondimensional distance from the

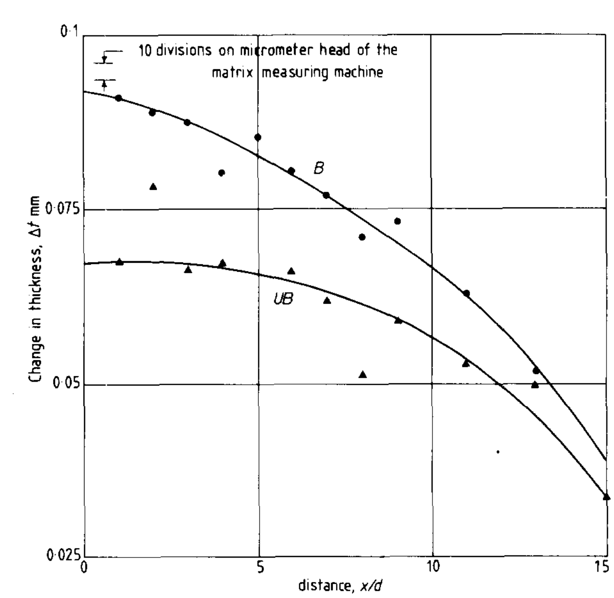

Fig. 6. Sublimation mass transfers with and without blowing after 2 hr ($M = 0{\cdot}5$, $Re = 3{\cdot}48 \times 10^4$)

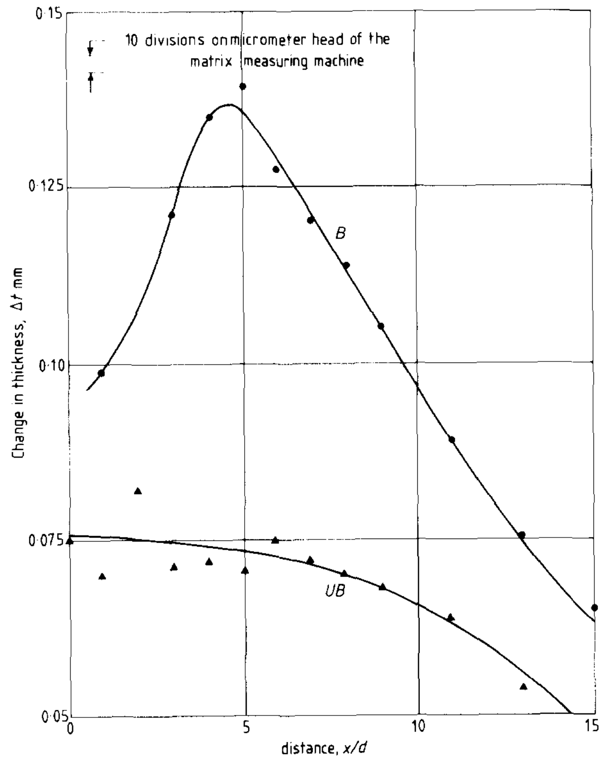

Fig. 7. Sublimation mass transfers with and without blowing after 2 hr ($M = 1{\cdot}0$, $Re = 3{\cdot}48 \times 10^4$)

slot, x/d, for the appropriate value of the blowing parameter M. The curves labelled UB and B refer to the unblown and blown sections, respectively. For the no blowing situations, the mass transfer curves (UB) are nearly identical, the relatively small differences between the curves being attributed to variations in the nature of the sublimating material and the conditions of the particular test.

The local mass transfer with blowing (curves B) is clearly dependent on the value of M, the blowing parameter, and shows a marked increase with increase in M. Furthermore, the shape of the B curves changes as M increases, and when $M = 1$, the curve exhibits a maximum point in the region about 5 slot widths downstream. This latter characteristic is consistent with the results of numerical analyses being conducted on this problem. At sufficiently large blowing rates and with the secondary flow injection perpendicular to the surface, there exists a recirculation zone immediately downstream of the slot. Large transfer rates then occur in the neighbourhood of the reattachment point, beyond which the transfer rate decreases monotonically in the region of the ensuing boundary layer flow. For the relatively small injection rates (see Fig. 5 for example), there appears to be very little effect on the magnitude of the local mass transfer which supports the simple assumption made previously, that the local heat transfer coefficient remains unchanged in film cooling application. (A further experiment at $Re = 8{\cdot}63 \times 10^4$ and $M = 0{\cdot}2$ for the same test period resulted in larger mass transfer rates but again showed little difference between the blown and unblown cases).

All the curves presented in Figs. 5, 6, and 7 refer to data obtained from measurements on one side of the slot. To test that these data represent those for the symmetric flow geometry, a separate test at $M = 0{\cdot}5$ was conducted and measurements made on both sides of the slot. Good symmetry of the mass transfer distribution was obtained indicating that the cylinder was positioned correctly in the wind tunnel.

Figures 5, 6, and 7 are very useful for demonstrating the effect of fluid injection by blowing through a slot on the magnitude of the local heat transfer coefficient. However, for comparison purposes, eq. (2) may be employed and this has been done by plotting the ratio $\Delta t_B/\Delta t_{UB}$ against the distance x/d as shown in Fig. 8. Bearing in mind that the geometry and method of injection plays an important role in this problem, the data of Goldstein (**1**) have been included. Goldstein's results refer to near tangential injection to a flow along a plate presumably in the zero pressure gradient. In the present investigation, the stream velocity increases almost linearly in the vicinity of the injection point and the associated pressure gradient is negative. Despite these differences in external flow conditions, comparison between the two cases is warranted. In Fig. 8, the ordinate $\Delta t_B/\Delta t_{UB}$ is equivalent to St_B/St_{UB} which has been adopted by Goldstein (**1**) affording a direct comparison between the mass and heat transfer result.

It will be observed that in both sets of data, the ratio increases with increasing M at any given location. At low blowing rates and for x/d less than about 10, the measurements are greater than those of Goldstein (**1**), and show that St_B/St_{UB} increases with increasing x/d whereas Goldstein's results are basically constant. At intermediate blowing rates the present measurements are greater than those of Goldstein (**1**) but show the same trends. At larger blowing rates, and for $4 < (x/d) < 10$, the agreement with Goldstein's results is very good although the present measurements show a maximum for St_B/St_{UB} at x/d approximately equal to 4 which is not apparent in the data of Goldstein (**1**). At large blowing rates the difference in the shapes of the curves may be accounted for principally by the difference in the methods of injection. As explained previously, normal injection results in a recirculatory

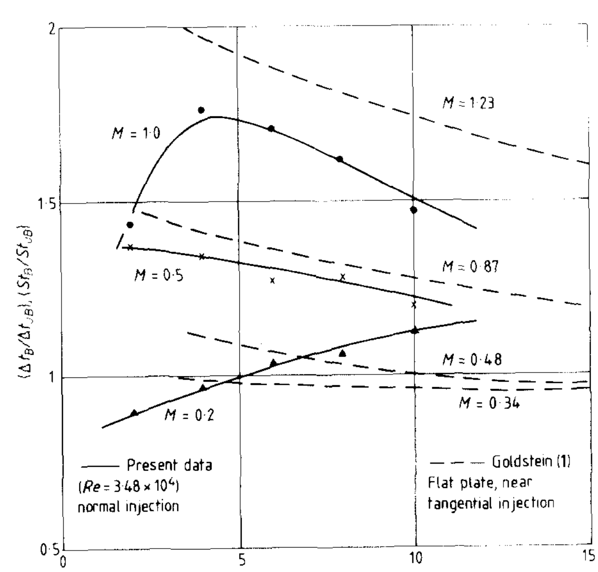

Fig. 8. Relative magnitudes of the local mass and heat transfer coefficients with and without blowing for various values of the blowing parameter M

pattern of flow downstream of the slot resulting in the local maximum value of transfer coefficient.

It is evident therefore that fluid injection may cause increases in the local heat or mass transfer coefficient of the order of 100 per cent in the range of blowing parameter considered.

The main purpose of the present investigation is to develop an experimental technique to predict heat transfer in film-cooling applications. The present results substantiate the adoption of the 'relative mass transfer method' since the accuracy in measuring the local thickness of the sublimating material is an order of magnitude better than that obtained using thermocouples to measure temperature. Apart from the error introduced by the installation of thermocouples particularly when they are closely spaced, lateral heat conduction and radiation effects aggravate the problem. A further refinement to the mass transfer technique would be to make a series of measurements after specified times of sublimation. Remembering that under steady state conditions, the change of thickness must be directly proportional to time, a number of measurements could be made and a mean value of the mass transfer rate calculated. In this way errors incurred using a single measurement would be reduced and the accuracy of the determination of the mass transfer rate would be improved even further. Reference to Fig. 7, however, suggests that at large blowing rates a single measurement after a two hour period is adequate. The curves with and without blowing are well defined in this case and the increase in the change of thickness effected by blowing is very much larger than the minimum division on the comparator.

CONCLUSIONS

A novel mass transfer experiment has been designed and conducted to determine the effect of fluid injection on the local heat transfer coefficient near the leading edge of a cylinder in cross flow. The purpose of the experiment is primarily concerned with the prediction of heat transfer to film-cooled turbine blades.

Simultaneous measurement of local mass transfer with and without blowing has been effected with a view to eliminating the use of the properties of the sublimating material. Another major advantage of the present technique is that the measurements with and without blowing are conducted under identical mainstream flow conditions.

It has been found that fluid injection may result in significant increase in local heat or mass transfer coefficient. In particular, for a Reynolds number of $3{\cdot}48 \times 10^4$ and with an injection velocity equal to the mainstream velocity, the increase is 75 per cent and this occurs about 5 slot widths downstream. For small injection rates there is only a small change in transfer rate and this may be ignored in heat transfer studies following earlier practice.

In the present investigation, injection was made to occur radially outwards at the leading edge for the purpose of comparison with the results of a theoretical analysis which is currently being made by one of the authors. Future experimental investigations will include studies of the influence of the location of the source of blowing, three-dimensional geometries using discrete holes, angle of injection and variation in velocities, and turbulence level in the mainstream.

Although the present investigation has been concerned specifically with heat and mass transfer in the film-cooling situation, use may be made of the technique in other cases. For example, the influence of promoters and secondary surface on transport processes may be studied using a similar method.

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