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NUMERICAL SIMULATION OF HYPERSONIC LAMINAR FILM COOLING

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Abstract. A computational study has been performed to investigate the effectiveness of film cooling in hypersonic laminar flows. First three different primary flow conditions are used for validation purpose. Then five coolant injection rates and three slot heights are examined. Both the primary and the coolant flow are air. A uniform boundary condition at the slot exit is found to be inaccurate for predicting heat transfer rate while the extended coolant inlet is proved to be much better. An isothermal wall is applied in this study. The computational results are compared with the experimental results and good agreement is achieved.

Key words: film cooling, hypersonic laminar flow, computational fluid dynamics.

1 INTRODUCTION

Film cooling introduces a secondary fluid into the primary flow stream in order to decrease the heat transfer rate from the primary flow stream to the solid wall or decrease the wall temperature. With the wall surface temperature at a lower level, less expensive materials can be used in structural fabrication. For example, blades of gas turbines, scramjet intake surfaces and combustor walls of high-speed vehicles, rocket nozzles and the surfaces of rockets usually work under high heating loads.

A film cooling model was first described by Stollery *et al.*[1] Three separate regions were recognised in film cooling using coolant injection through a slot over a flat plate. Just downstream of the injection slot, there is a mixing-layer region, which is called the "potential core" region. In this zone, the wall temperature remains close to the coolant gas temperature. The cooling length can be defined here as the length downstream of the slot where the adiabatic wall temperature is equal to the injectant stagnation temperature.[2] A "wall-jet" region exists after the "potential core" region, where the velocity profile is similar to that of a wall jet. Farther downstream, there should be a fully developed boundary-layer when the difference between the coolant and the primary flow streams disappears. For coolant and primary gases of similar density the relative length of the three regions is governed mainly by the velocity ratio between the coolant flow and the primary flow, u_c/u_p. When $u_c \gg u_p$, a simple jet model suggested by Spalding[3] for the second zone may be appropriate. When $u_c < u_p$, the second region is non-existent. Although some experiments have been done to investigate the former condition, the latter one is more commonly used in both experiment and practice.

Many experimental results[2,4–9] have been published on hypersonic film cooling. Film cooling effectiveness was found to be concerned with many parameters. Many researchers offered different empirical equations to predict the effectiveness of film cooling. But usually such equations are only valid in a narrow scope related to similar conditions used in the experiment. Different parameters such as slot height, lip thickness, flow density and velocity ratios between the primary and the coolant flow, a coolant gas different from the primary one were studied. With the development of computational techniques and the computer hardware, some computational results of supersonic film cooling[10–13] were also published. The adiabatic wall boundary condition is applied in most of the previous studies with the film cooling effectiveness defined as a non-dimensional temperature as follows

$$\eta = \frac{T_{ad,w} - T_\infty}{T_c - T_\infty}. \tag{1}$$

$T_{ad,w}, T_c, T_\infty$ in Eqn. (1) represent adiabatic wall, coolant and freestream flow temperatures, respectively. This definition is applicable when adiabatic conditions can be observed in the experiment. The equation requires the temperature of the primary flow to be low and the surface investigated does not need additional regenerative cooling.

In this paper, the computational work based on Richards' early experimental work[5] on hypersonic laminar film cooling has been performed to investigate the effect of the coolant injection rate and the slot height in hypersonic laminar film cooling problem. A conical nozzle was used in the experiments for the laminar case in a hypersonic wind tunnel ($M = 10$). In the experiments, the useful running time was only approximately 40 ms. Thus the isothermal wall boundary condition is used instead of the adiabatic wall boundary condition along with the equivalent definition of film cooling effectiveness.

2 NUMERICAL METHODS AND COMPARISONS WITH EXPERIMENTAL DATA

The PMB2D code developed at the University of Glasgow is used in this study to examine film cooling in hypersonic laminar flow. This code is a generic CFD code which has been used to successfully model steady and unsteady flows including aerofoils, wings, jets and cavities in subsonic and transonic flows. A cell-centred finite volume discretisation method is employed to solve the Reynolds-averaged N-S equations. Details of the code can be found in the paper presented by Badcock *et al.*[14]

Primary flow conditions are extracted at the slot exit as listed in Table 1. In the prelimary work, three flat plate cases were set up for validation purpose. Good agreement was achieved for both the static pressure and heat transfer rate distributions.

After that, three film cooling cases are set up under the same slot height, 1.2192 mm, and the same coolant injection rate, 5.07×10^{-4} kg/s. The primary flow conditions

Case	M_∞	Re/m	$P_\infty(Pa)$	$T_0(K)$	$T_\infty(K)$
1	9.90	6.46×10^6	476.00	1290.00	62.62
2	9.90	5.45×10^6	341.00	1170.00	56.79
3	9.90	4.24×10^6	214.00	1030.00	50.00

Table 1: Three different primary flow conditions calculated from the experiments

are the same as listed in Table 1. Since in the experiments, coolant flow choked at the slot exit, a uniform boundary is first set up at the slot exit with density, velocity and pressure values ($\rho_c = 1.166 \times 10^{-2}\, kg/m^3, M_c = 1, p_c = 809.34\, Pa$) calculated from the experimental data. The lip is set to zero in these three cases. The computational domain is sketched in Fig. 1 without the lip and the coolant inlet extension. Heat transfer rate is compared with experimental results in Fig. 2(a) in which the symbols indicate the experimental data while lines indicate computational data. Although heat transfer rate is under-predicted in all three cases, it is clear that film cooling is really effective in the area just downstream of the slot. The wall surface is fully protected in this small area.

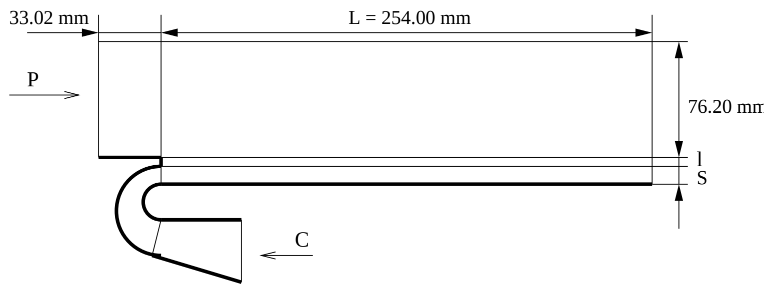


Figure 1: Film cooling geometry description

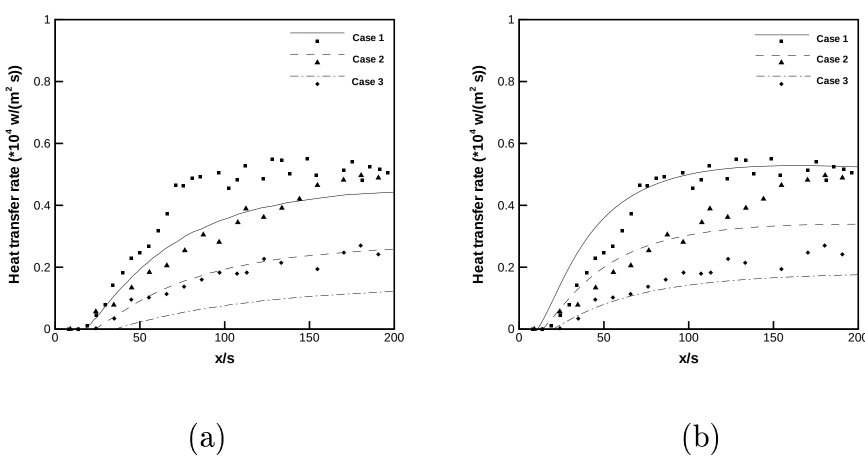


Figure 2: (a) Heat transfer rate comparison using uniform boundary at slot exit
(b) Heat transfer rate comparison with coolant inlet extension and lip

In order to improve the heat prediction, the slot inlet is extended as described in Fig. 1. Since the original detailed geometry data was lost, a coolant inlet of approximate dimensions is set up from a sketch drawn by Richards.[5] Also the lip is simulated with the thickness $0.0508\,mm$. Coolant injection rate is kept constant when extending the slot inlet. The prediction of the heat transfer rate given in Fig. 2(b) is greatly improved when compared with uniform slot exit boundary calculation in Fig. 2(a). In general, the agreement is fairly good for all three cases. For case 2, experimental error may explain the big difference far from the slot exit. Discrepancy in the near slot area is noticeable in cases 1 and 2. The velocity profile at the slot exit is found not to be parallel to the primary flow so it is obvious that the uniform velocity profile parallel to the primary flow previously used is not correct. But since the original coolant inlet geometry was lost, the curve inlet is only roughly simulated. This causes the flow parameters still not to be accurate at the slot exit which may signal why some discrepancies can still be observed in the near slot area.

For case 1, velocity profiles at eight different positions downstream of the slot are shown in Fig. 3. Just downstream of the slot, two boundary layers belonging to the primary flow and the coolant flow respectively, are observed. The development of the mixing layer can be clearly observed from 0.5s to about 20s downstream of the slot. After that, the separate identity of the coolant and the primary flow stream disappears. The two boundary layers finally become a single layer, which signals the coolant and the main flow is fully merged. It is seen in Fig. 2(b), only after about 10s downstream of the slot, does the heat transfer register and then start increasing. This relates to the shape of the velocity profiles obtained.

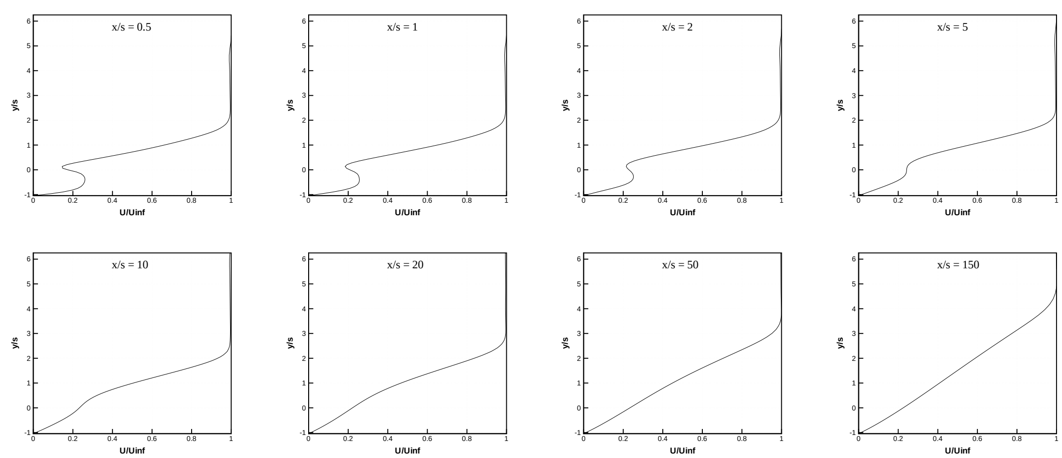


Figure 3: Velocity profiles of laminar film cooling problem

2.1 Increasing coolant injection rate

Five different coolant injection rates listed in Table 2 from 2.95×10^{-4} to $7.33 \times 10^{-4}\,kg/s$ are computed under the same flow conditions as Case 1 in Table 1.

Mach number contours of the flow are presented in Fig. 4. The five Mach number contours are for laminar film cooling with the coolant injection rate increased. Here the Mach number contours show that separated coolant flow extends downstream as the coolant flow injection rate is increased. Thus heat transfer rate decreases and film cooling effectiveness increases with increased coolant injection rate. This is because as the coolant flow injection rate is increased, more energy and momentum are contained in the coolant flow stream. The unmixed coolant flow penetrates the primary flow further from the slot. Thus the convective heat transfer rate between

LFC Case	$\dot{w}_c(kg/s)$	$\rho_c(kg/m^3)$	M_c	$p_c(Pa)$
1	2.95e-4	1.07e-2	0.11	885.50
2	4.08e-4	1.47e-2	0.11	1226.08
3	5.07e-4	1.83e-3	0.11	1521.25
4	6.10e-4	2.21e-3	0.11	1839.12
5	7.33e-4	2.65e-3	0.11	2202.40

Table 2: LFC cases with different coolant injection rates.

the primary flow and the wall surface is reduced. Film cooling effectiveness therefore increases.

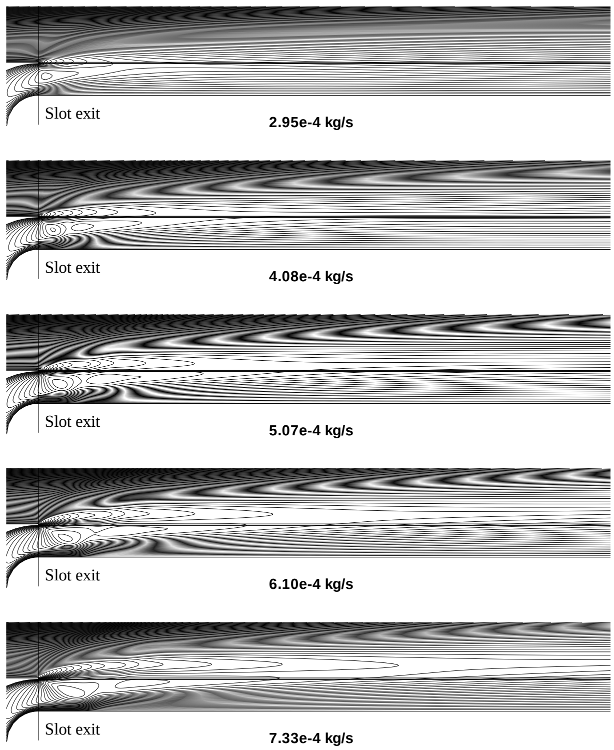


Figure 4: Mach contours of different coolant injection rates

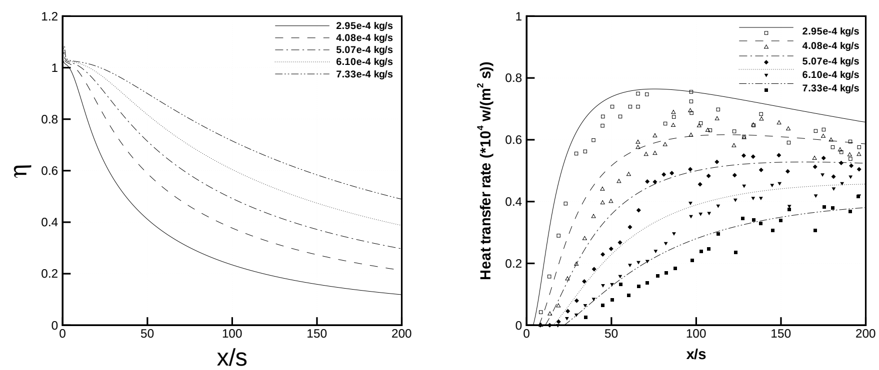
Under all the five coolant flow injection rates, the coolant flow is found to be choked at the slot. Then the coolant flow will accelerate and become supersonic with expansion downstream of the slot. Thus, an effective slot height s' was used by Richards[5] as coolant layer height in application of the discrete layer theory. Fig. 3 and Fig. 4 also show this phenomenon. Just after the slot, there is no upper wall surface so that expansion can occur. It is demonstrated that it is not easy to calculate an effective slot height from the computational results.

As mentioned before, the experimental duration time was only about $40ms$, so the film cooling effectiveness was defined directly from the heat transfer rate, not the wall temperature.

$$\eta = 1 - \frac{\dot{q}_c}{\dot{q}_0} \tag{2}$$

$\dot{q}_c$ and $\dot{q}_0$ in the above equation represent heat transfer rates with and without coolant injection, respectively. The zero coolant injection case is the flat plate case in this study.

From Fig. 5(a), it is clear that increasing the coolant injection rate will provide improved cooling effectiveness. Also the film remains fully effective some distance downstream of the slot (about 10s in Fig. 5(a) for $\dot{w}_c = 5.07 \times 10^{-4}\,kg/s$). Then mixing between the coolant flow and the primary flow becomes stronger, which makes the effect of film cooling decrease. But the effectiveness remains high even far from the slot. For example, the effectiveness is about 30% for the mid range coolant injection rate 200 slot heights downstream of the slot. The same conclusion was achieved not only in hypersonic[2] but also in supersonic[15,16] and subsonic film cooling.[17,18]



(a) (b)

Figure 5: (a) Laminar film cooling effectiveness of different coolant injection rates
(b) Heat transfer rate comparison of different coolant injection rates

Heat transfer rates are compared with the experimental data in Fig. 5(b). After 100 slot heights, the agreement is quite good while in the near slot area the computational results are higher than the experimental results. As mentioned above, inaccurate inlet geometry could play an important role here. Also in the experiments, it was found that it is likely to be very difficult to obtain fully two dimensional injection of the coolant. Furthermore the flow conditions used in the computation are extracted from the experimental data which may cause some minor uncertainties.

2.2 Increasing the slot height

The second factor investigated here is the slot height. Three different slot heights ($s = 0.8382, 1.2192, 1.6002\,mm$) are examined under the same flow condition as Case 1 in Table 1 with constant coolant injection rate ($\dot{w}_c = 5.07 \times 10^{-4}\,kg/s$).

The computational results in Fig. 6 show us that the effectiveness of film cooling can only be slightly increased while increasing the slot height. Increasing the slot height will increase the thickness of the unmixed coolant flow after injection. This will increase film cooling effectiveness. But as mentioned before, coolant flow chokes at the slot position so the coolant speed stays constant. Also, under the same coolant injection rate, when the slot height is increased, the density and the pressure will decrease which will diminish the film cooling effectiveness. So the effect of slot height has only a marginal effect here. In the experiment, the same results were observed.

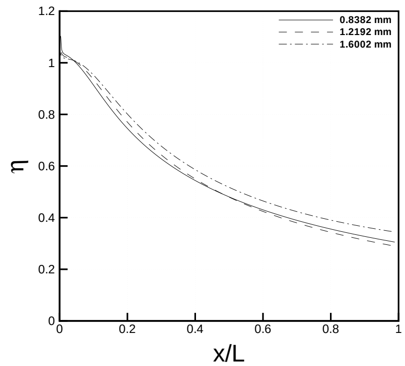


Figure 6: Laminar film cooling effectiveness of different slot heights

3 CONCLUSIONS

Film cooling in hypersonic laminar flow has been numerically investigated for three primary flow conditions, five coolant injection rates and three slot heights. With the coolant inlet extended, heat transfer rate is better predicted than setting up the uniform boundary at the slot exit. The following conclusions are drawn:

(1) Primary flow conditions are very important. Under the same slot height and the same coolant injection rate, higher effectiveness can be obtained when total temperature and static pressure of the primary flow decrease.

(2) Film cooling in hypersonic flow can be very effective in laminar flow. At some distance downstream of the slot the effectiveness is fully effective. The distance in this study is about 10 times the slot height. The effectiveness drops due to mixing between the coolant and the primary flow streams. In laminar flow, the effectiveness was found to be still quite high even far downstream of the slot.

(3) Increasing the coolant injection rate can obviously increase the film cooling effectiveness for laminar cases. Another cooling method such as regenerative cooling is suggested to be used in combination with film cooling.

(4) Slot height does not play an important role under the flow conditions here. This factor can be ignored when designing the structure of the film cooling system.

(5) Coolant flow expansion was observed just downstream of the slot position. The inlet extension is found to be necessary to improve the CFD results.

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