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Numerical Study of Jet Interaction in Film Cooling on an Adiabatic Flat Plate

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Abstract—*Understanding of jet interaction in film cooling is crucial for design of combustion chamber cooling in modern gas turbine engines. This study mainly focuses on physics of jet interaction in film cooling between forward- forward and backward-backward injection holes. In this paper numerical simulation of film cooling on an adiabatic flat plate is carried out for two different configurations composed of only one injection hole and two injection holes. Each configuration consists of only forward injection holes and only backward injection holes. This study is carried out at velocity ratio of 0.5 and 1.0 for both configurations with cooling holes inclined at an angle of 30^o with respect to the mainstream. To compare cooling performance and to understand flow physics of jet interaction, adiabatic film cooling effectiveness is calculated on the adiabatic wall. There is an increase in adiabatic effectiveness obtained on downstream of second hole due to jet injection from first hole. This increase is more in the case of forward injection configuration than that in backward injection configuration. Further, this additional cooling effectiveness obtained on second hole decreases with increase in velocity ratio for both the configurations. At high velocity ratio(1.0), it becomes same on second hole as that of first hole in case of forward injection and even lesser than that of first hole in backward injection configuration. A drop in average effectiveness is observed between trailing edge and center of the second hole due to the injection from first hole in forward injection configuration. This decreases with increase in velocity ratio. This drop is not observed in case of backward injection.*

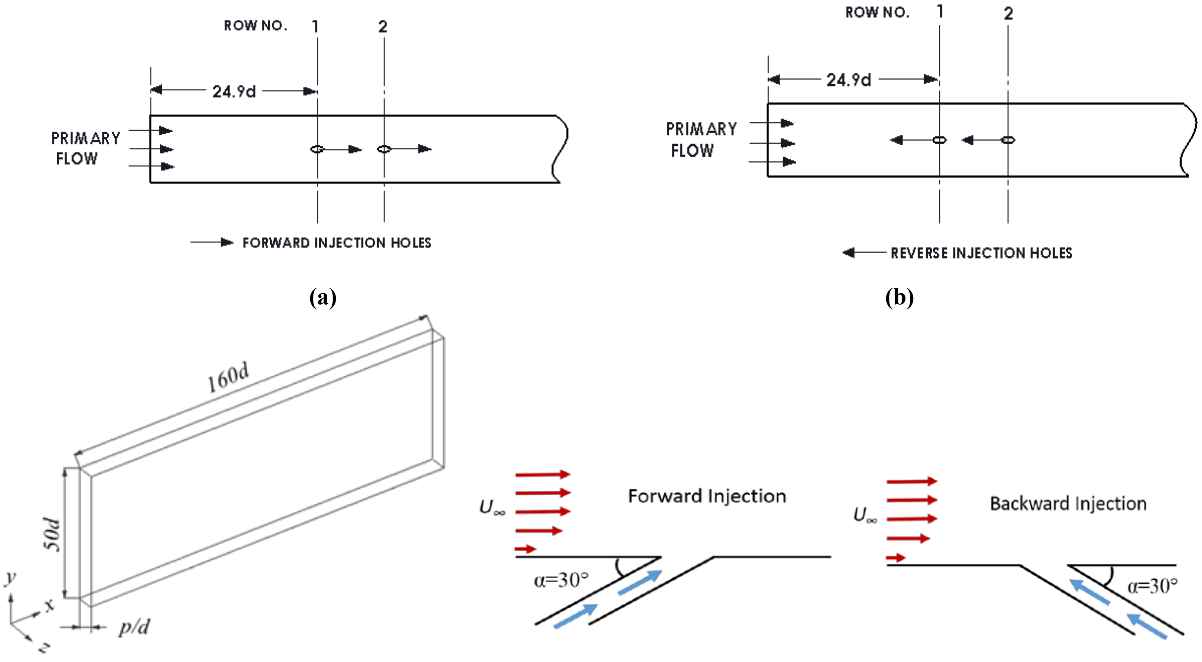
1. INTRODUCTION

Numbers of rows of injection holes are used in the film cooling of gas turbine components. The turbine designers are always concerned with effective use of the cooling air [1] for which they may have freedom of choice of velocity ratio, density ratio, angles of orientation and row spacings[2], but there is comparatively less data published in open literature to make his decision. It is impractical to conduct experiments to choose the selective combination from large range of possible parameters. Film cooling is generally achieved by the use of cylindrical or shaped holes. In case of forward injection there are formation of kidney vortices and jet lift off with cylindrical holes which limits their film cooling performance at high velocity ratios which is not with the case of shaped holes due to their diffusive exit. However, cylindrical holes have been more commonly researched as they are simple and cheaper to fabricate [3]. Generally adiabatic flat plates are used for numerical and experimental studies on film cooling [4] to reduce complexity. Although there is substantial literature available on full coverage film cooling with forward and backward injections, but very few literatures are available which studies the injection from a single hole and its effect on downstream hole. Cooling effectiveness downstream of hole may be affected by the coolant jet from preceding hole depending upon velocity ratio. Hence, there is a scope to study the effect of jet interaction between the two holes with forward and backward injection configurations. In this paper average film cooling effectiveness and lateral distribution have been calculated in the proximity of two hole region to study the effect on cooling performance of second hole due to injection from first hole.

2. METHODOLOGY

2.1 Computational Model

A 3Dcomputational model is studied for forward and reverse injecting hole configurations Figure 1(c).The domain consists of single hole and two hole configurations injecting at velocity ratios 0.5 and 1.0 in forward and backward directions. The forward and reverse injection configurations have been shown in Figures 1(a)-(b). When coolant is being injected only from first hole it is called case 1, when injected only from second hole it is called case 2 and it is called case 3 when injection is carried out from both the holes. Further, these cases are classified based upon the direction of injection of coolant from the hole and the velocity ratio. Case 1 with forward injection at velocity ratio (*VR*) 0.5 means that first hole is injecting in forward direction with a *VR*of 0.5. Other cases are established on the similar manner. The holes are of 1.0mm(*d*) diameter and are inclined at an angle of 30^0 with respect to the flow of mainstream as shown in Figures 1(d)-(e). Air has been used as a working fluid for both primary and secondary flow. The first hole is at a distance of 24.9mm from the trailing edge of the plate in the stream wise direction. Hole-to-hole spacing is 9.8 mm. The height of the domain (Figure 1(c)) is 50*d* (y-direction), length is 160*d* (x-direction) and width is 9.8*d* (z-direction).



(a) (b)

(c) (d) (e)

Figure 1: (a) Forward injection configuration; (b) Backward injection configuration; (c) Computational domain in 3D; (d) Forward injection hole; (e) Backward injection hole

2.2 Governing Equations

The conservation equations of mass, energy, momentum and state are solved using ANSYS FLUENT. The equations can be found in detail in Versteeg et al. [5]. 'Adiabatic film cooling effectiveness' (η_{ad}) is a non-dimensional parameter used to judge and compare the results of film cooling.

$$\eta_{ad} = \frac{T_g - T_{aw}}{T_g - T_c} \tag{1}$$

Where;

T_g= Mainstream temperature (Primary flow)

T_{aw} = Temperature of the adiabatic wall

T_c= Temperature of the coolant (Secondary flow)

2.3 Numerical Computation

The generation of grid is done by Gambit 2.4.6 pre-processing software. Meshing has been done on the adiabatic wall and then is swept through the vertical height of the domain. The mesh generated is very fine around the coolant hole to capture the boundary layer in detail. Non-dimensional boundary layer thickness (y^+) values are controlled below 1.0 throughout the adiabatic wall. Realizable *k-ε* turbulence model with enhanced wall treatment has been used in this study [6, 7]. The flow used is incompressible in the 3D computational domain so that the value of Mach number does not exceed 0.3 at any point.

Following convergence criterion is used;

i) All the residual values apart from energy should be below 10^{-4} which should be less than 10^{-6}.

ii) Mean surface temperature of wall should become almost constant for the consecutive iterations.

2.4 Boundary Conditions

Velocity ratio (*VR*) is a non-dimensional parameter defined as;

$$VR = \frac{V_c}{V_g} \tag{2}$$

Where, V_c= Velocity of coolant (secondary flow) and V_g= Velocity of mainstream (primary flow).

Velocity of mainstream (V_g) is kept constant at 50 m/s while that of the coolant from injection hole (V_c) varies according to the velocity ratio. The temperature of the mainstream (T_g) is fixed at 350 K while that of the coolant (T_c) is kept at 300 K. The pressure at outlet is kept at static atmospheric pressure (1 atm). Turbulence intensity of 0.5% is used for the mainstream and the coolant. Turbulence length scale is 3% of the height of primary flow inlet is used for flow inlet boundary condition. No-slip condition is assumed at the boundary of the adiabatic wall. Top and transverse planes are considered as 'symmetry' in the domain.

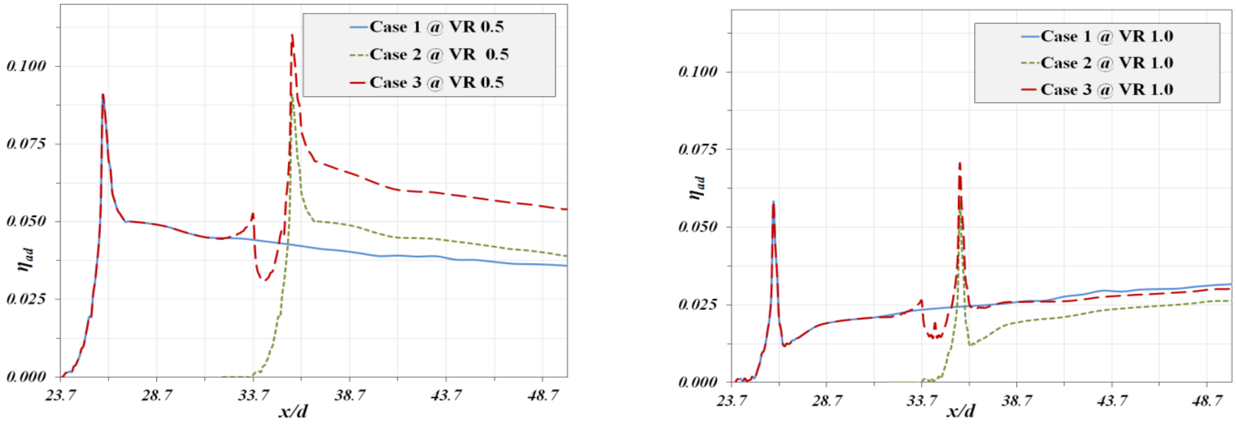
2.5 Grid independence study and validation of numerical approach

The validation of numerical approach andgrid independence test is performed with forward injection cooling holes at *VR*=0.5 and outcome of numerical investigation is compared with the experimentally available results of Scrittore et al. [8] at *VR*=3.2. Details of grid independence study and validation of numerical approach can be found in companion papers [9, 10].This is an extended study of our previous work. The same results have been adopted for this study of single and double row of cooling hole.

3. RESULTS AND DISCUSSION

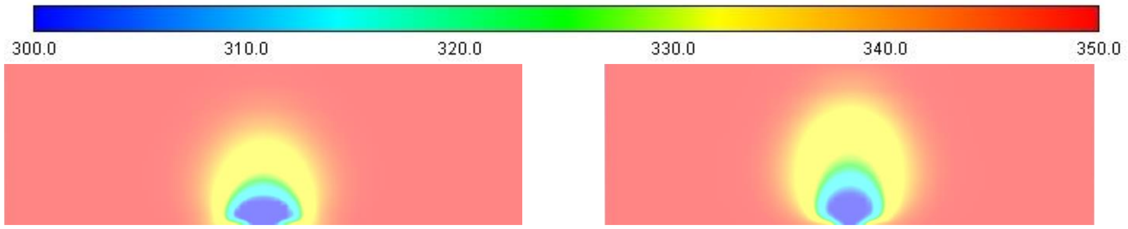
3.1 Laterally Averaged Film Cooling Effectiveness

The laterally averaged film cooling effectiveness at forward injection has been shown in Figures 2(a)-(b) and at reverse injection in Figures 4(a)-(b). Temperature contours on yz plane for forward injection are shown in Figures 3(a)-(b). The laterally averaged effectiveness has been captured on rows starting from the trailing edge of the first hole at a stream wise (x) distance 0.1 mm near the hole and at a distance of 1 mm on rows away from the holes so as to obtain fairly accurate results.



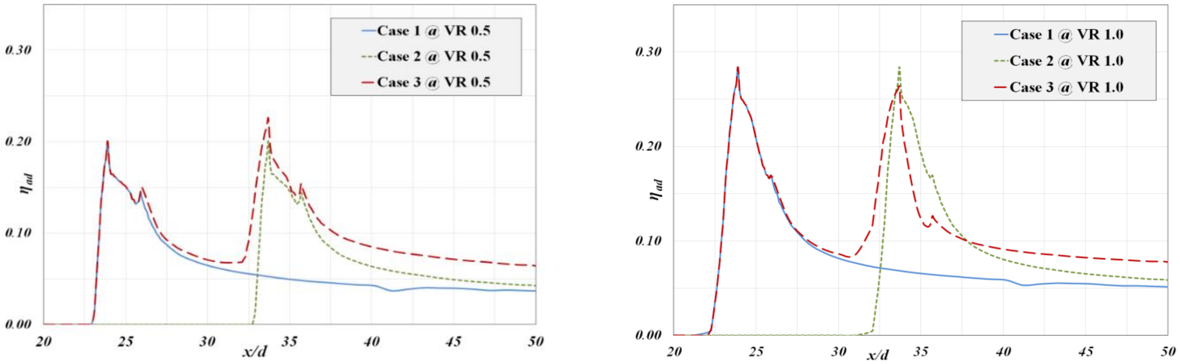
(a) **(b)**

Figure 2: Distribution of laterally averaged cooling effectiveness for forward injection (case 3) at *VR* (a) 0.5; (b) 1.0



(a) (b)

Figure 3: Temperature contour on yz plane at the leading edge of second hole for forward injection (case 3) at *VR* (a) 0.5; (b) 1.0



(a) (b)

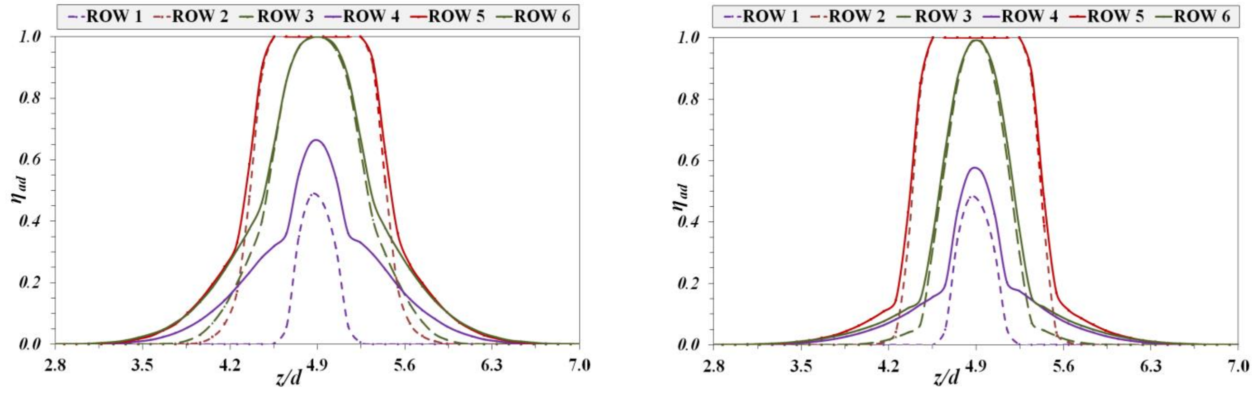
Figure 4: Distribution of laterally averaged cooling effectiveness for backward injection (case 3) at *VR* (a) 0.5; (b) 1.0

Forward injection in case 3 gives additional effectiveness when compared to case 2. But this additional effectiveness is more for *VR*=0.5 and almost negligible for *VR*=1.0 in forward injection configuration. Formation of kidney vortices in forward injection at the hole has been observed. These kidney vortices tend to bring the hot mainstream gas thus reduces the average effectiveness. In case 3 of forward injection a drop in average effectiveness has been observed at the trailing edge (33.7*d*) of the second hole (Figures 2(a)-(b)). This drop continues till the center of the hole after which the effectiveness starts increasing. This can be explained by the stagnation of the secondary flow when it meets the injection from second hole. Also the secondary flow starts lifting with the injection of second hole in this region. However, under the influence of injection from second hole the effectiveness starts increasing from the center. In case of reverse injection, it has been observed that *VR* of 1.0 gives better adiabatic effectiveness. Secondary flow has a tendency to move backwards (depending upon the velocity ratio) from the trailing edge in the stream wise direction but due to the incoming mainstream the flow turns around and gets carried away by the mainstream in the forward direction. Due to this behavior the lateral coverage of the secondary flow on wall is more. In the presence of mainstream flow, the injection gets suppressed and attaches early to the wall early giving better effectiveness. When case 3 and case 2 are compared, it is observed that the injection from first hole has varied impact on the injection from second hole depending on the velocity ratio. There is a slight increase in effectiveness upstream of the second hole up to the leading edge of the first hole. This is due to the restriction to the flow of hot gases from the mainstream into this region under the impact of injection from second hole. On moving downstream from the second hole, the additional effectiveness forcase 3 decreases with increase in velocity ratio. The secondary flow from first hole lifts off along with the injection from second hole. Due to this detachment there is a decrease in added effectiveness. For *VR*=0.5, this decrease in added effectiveness is less. However in case of *VR*=1.0, the added effectiveness is negative i.e. case 2 shows high averaged effectiveness than case 3 upstream from the second hole. This anomaly is because of intensity of injection from first hole at *VR* 1.0 which is much more than that in *VR*=0.5 and hence the secondary flow gets carried away. However at the leading edge of second hole, the secondary flow reattaches and added effectiveness of case 3 becomes more than that of case 2 at *VR*=1.0.

Forward injection is compared with reverse injection. It can be seen that reverse injection gives a much better lateral average effectiveness. In forward flow, due to the formation of kidney vortices, the hot mainstream gas enters and hence decreases cooling effectiveness. However in case of reverse injection the kidney vortices are not formed and the secondary flow gets attached early to the plate. Also in reverse injection there is more lateral coverage. With increase in velocity ratio, reverse injection shows an increase in lateral average effectiveness while the average effectiveness in forward injection decreases as it has a tendency to lift off from the wall and at highervelocity ratio, this tendency increases. In case 3, at *VR*=0.5, added effectiveness due to the injection from first hole at downstream of the second hole is more in the case of forward injection when compared to reverse injection.

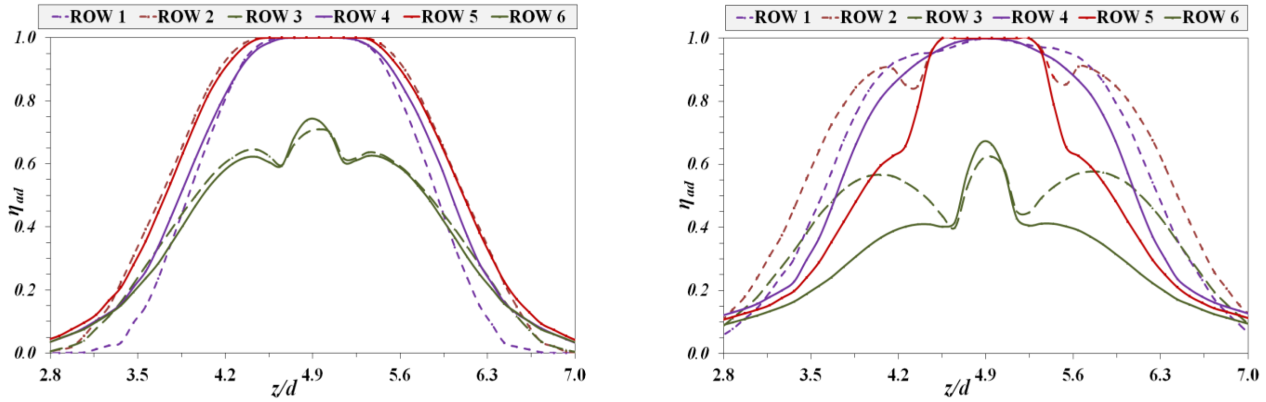
3.2 Lateral Film Cooling Effectiveness

The lateral distribution of film cooling effectiveness for case 1 and 3 has been plotted on different rows (z direction) at for forward and backward configuration in Figures 5(a)-(b) and 6(a)-(b), respectively. Row 1 is on the trailing edge (z direction) of the first hole, 2 on the middle and 3 on the leading edge. Similarly, row 4 is on the trailing edge of the second hole, 5 on the middle and 6 on the leading. In forward injection configuration, case 3 shows a better overall effectiveness at *VR* 0.5 than case 1. With increase in velocity ratio, the lateral effectiveness curve for case 3 starts approaching case 1. At a *VR* 1.0 the effectiveness curve of case 3 and case 1 almost overlaps, showing that there is no significant impact of injection of first hole on the second hole. This is due to the lift off the secondary flow over the second hole showing no improvement in cooling over the wall. However the lateral spread is increased on the second hole due to the injection from the first hole which is evident from the figures. In backward injection configuration, the lateral spread increases with increase in velocity ratio which can be seen from the difference in the width of the curve in figures 6(a) and 6(b). At lower *VR*=0.5, the curves of case 1 and case 3 almost overlaps, implying that thereis no significant advantage of injection from hole 1 on hole 2. However, at *VR*=1.0, the lateral spread on second hole due to the injection from the first hole becomes even lesser than that on the first hole. This confirms the decrease in average adiabatic effectiveness of case 3 when compared to case 2 downstream of the second hole (Figure 4(b)).



(a) **(b)**

Figure 5: Comparison of lateral cooling effectiveness in forward injection configuration for case 1 and case 3 at *VR* (a) 0.5; (b) 1.0



(a) **(b)**

Figure 6: Comparison of lateral cooling effectiveness in backward injection configuration for case 1 and case 3 at *VR* (a) 0.5; (b) 1.0

4. CONCLUSION

Additional effectiveness is obtained downstream of second hole due to the injection from first hole in forward injection case. This is more at low velocity ratio. At high velocity ratio, the coolant stream from hole lifts off at second hole, thus giving no significant advantage in cooling effectiveness. In reverse injection no such additional effectives on downstream of second hole is observed. In fact, the effectiveness downstream of second hole decreases at VR=1.0 which is evident from lateral and average lateral distribution of cooling effectiveness. A drop in effectiveness is observed in forward injection when secondary flow from first hole encounters injection from second hole. This can be justified by the momentary stagnation of coolant flow at the trailing edge of the second hole due to the intensity of jet at second hole. However the influence of injection from second hole causes a slight increase in average effectiveness up to the leading edge of the first flow. This is due to the tendency of injection to flow backwards.

REFERENCES

[1] Goldstein R. J.,"Film cooling",*Adv. Heat Transfer*,**7,** 1971,pp. 321-79.

[2] Afejuku W.O., Hay N., and Lampard D., "The Film Cooling Effectiveness of Double Rows of Holes", 1980,***J.**of Engineering for Power,* pp.601-06.

[3] Goldstein R.J., and Jin P., "Film cooling downstream of a row of discrete holes withcompound angle ASME",*J. Turbomach.* 123 (2), 2001, pp. 222-30.

[4] Tarchi L., Facchini B., Maiuolo F. and Coutandin D.,"Experimental investigation on the effects of a l large recirculating area on the performanceof aneffusion cooled combustor liner", 2012,*J. Eng. Gas Turbine Power* 134 (4), 041505.1–041505.9.

[5] Versteeg H. K., and Malalasekera W.,"Anintroduction to computational fluid dynamics: thefinite volume method",*second Ed. HarlowEngland: Pearson Education Limited,*2007.

[6] Sinha A. K., Bogard D. G. and Crawford M. E., "Film-cooling effectiveness downstream of a single row of holes with variable density ratio", *J. Turbomach.*, 113, 1991, pp. 442-49.

[7] El-Gabry L. A. and Heidmann J. D.,"Numerical study on the sensitivity of film cooling CFD results to experimental and numerical uncertainties", *Int. J. Comput. Methods Eng. Sci. Mech.*,14, 2013, pp. 317-28.

[8] Scrittore J. J., Thole K. A. and Burd S. W.,"Investigation of velocity profiles for effusion cooling of a combustor liner" *J. Turbomach.*,129 (3),2007, pp. 518-26.

[9] Mishra Mukesh Prakash, Sahani A. K., Chandel Sunil, and NegiBhawesh,"Enhancement of full coverage film cooling performance with opposite injection holes", *Mater. Today: Proc.* 5,2018, pp. 19517-28.

[10] Mishra MukeshPrakash, Sahani A. K., Chandel Sunil, and Mishra R. K., "Enhancement of full coverage film cooling effectiveness with mixed injection holes", *Int. J. Turbo Jet Engines,* 2018.