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Numerical Study of Film Cooling with Holes Injecting at Two Different Angles

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Abstract—*Full coverage film cooling is widely used in gas turbines to protect combustor liner from high temperature environment. In this paper numerical simulations of full coverage film cooling on an adiabatic flat plate is carried out for three different configurations composed of 15° injection holes, 30° injection holes and alternate rows of 15° and 30° injection holes. Each configuration consists of three variants composed of only forward injection holes, only backward injection holes and rows of cooling holes injecting in alternate backward and forward mix-directions. The study is carried out at three different velocity ratios of 0.5, 1.0 and 2.0 and at coolant-to-mainstream density ratio of about 1.0. Diameter (d) of each cylindrical hole is 1.0 mm. The holes are arranged in an array of 20 rows with equal span wise (p) and stream wise hole-to-hole pitch (s) of 4.9d. Adiabatic film cooling effectiveness is calculated along stream wise as well as lateral directions on the flat plate in order to compare the cooling performance of the different configurations. Film cooling performance of the configurations composed of backward injection holes and backward and forward mix injection holes are found very sensitive to the value of injection angle. Whereas cooling performance of configurations with only forward injection holes are poorly dependent on angle of injection. Cooling effectiveness is found strongly dependent on velocity ratio for all the configurations. Configuration with alternate rows of 15° and 30° holes with mix injection shows better cooling than the other two configurations with mix injection at high velocity ratio. Development of effusion film layer is also studied for the three configurations with forward, reverse and mix injections. Early transition of effusion film layer from developing stage to developed stage is seen only for configurations with forward and mix injection holes and at high velocity ratio.*

Keywords*: Film cooling, cooling effectiveness, forward injection, backward injection.*

1. INTRODUCTION

Turbine Inlet Temperature (*TIT*) is a major variable to influence gas turbine performance in terms of increased specific thrust or specific work output. It is being steadily increased and in modern turbines it is too high for combustor liner to withstand for the desired life and performance requirements [1, 2]. Combustor liner is necessarily cooled to safeguard it from high temperature environments. Full coverage film cooling is generally used to cool the combustor liner. In full coverage film cooling, relatively cool air is injected through an array of closely spaced tiny holes drilled in the wall which forms a protective cold layer on the wall and separates the wall from hot combustion products [3]. Two types of holes are generally used in film cooling: cylindrical and shaped holes. Due to expanded exit, shaped holes demonstrate better cooling than cylindrical holes in lateral direction. Shaped exit also reduces formation of kidney vortices jet penetration as seen with cylindrical holes at high blowing ratios [4, 5]. But cylindrical holes are very easy to manufacture due to their simple structure and also provide improved film cooling when injected in compound direction [6]. Therefore, various researches in film cooling are focused around cylindrical holes with compound angle injection.

Many studies are available in open literature to investigate various geometrical and aero-thermal parameters influencing film cooling performance such as number, distribution, injection angle and length-to-diameter ratio of film cooling holes and mainstream-to-coolant temperature ratio, pressure ratio, density ratio, blowing ratio etc. [7-9]. Scrittore et al. [10] conducted series of experiments for full coverage film cooling on flat plate with 20 rows of cylindrical holes equally spaced (p/d=4.9, s/d=4.9) in both stream wise and lateral directions. They carried out measurement of flow-field and adiabatic wall temperatures for a wide range of blowing ratio of practical use. The experimental results of their studies are very useful and are used to validate the CFD tool used in the present work.

Yang et al. [11] carried out parametric studies on various arrangements of cooling holes by varying span wise and stream wise hole-to-hole pitch at a fixed value of perforation percentage at various velocity ratios. They found that reduction in span wise hole-to-hole pitch not only favors the early formation of developed film layer but also enhances film cooling effectiveness. Hasan et al. [12] investigated film cooling performance of forward injection holes at different velocity ratios. They found strong influence of mass flow rate of coolant supply on film cooling effectiveness.

Among many shapes, angles and arrangements of film cooling holes, backward injection particularly applied to cylindrical holes, has been found to significantly improve film cooling effectiveness compared with the conventional direction of forward injection. Oguntade et al. [13] carried out experimental and numerical studies with backward injection. They demonstrated improved film cooling with backward injection over forward injection. Chen et al. [14] conducted experiments to investigate film cooling performance with backward injection for cylindrical and shaped holes. Their results demonstrated that reverse injection through cylindrical holes provides enhanced film cooling effectiveness, but this was not with shaped holes. Andrews et al. [15], in their study, compared effusion cooling performance with forward and reverse injection. Reverse injection resulted improved film cooling effectiveness as compared to forward injection holes at low coolant flow but not at high rate of coolant flow.

Kuldeep Shrama et al. [16] carried out experimental and numerical studies on film cooling with forward and backward injection with single row of cooling holes. The injection angle was varied from 30° to 60° and blowing ratio from 0.25 to 3.0. Pitch wise hole-to-hole spacing was three times the diameter of the hole. They concluded from their study that cooling with reverse injection was much better than with forward injection. They also reported that spread of coolant was more uniform in lateral direction for backward injection which mitigated hot patches between the cooling holes evident in forward injection.

Sehjn et al. [17] conducted experiments with two rows of cooling holes spaced 6 and 3times the diameter of the hole in span wise and stream wise directions respectively using pressure sensitive paint (PSP) method to measure wall temperature. They studied film cooling performance of three configurations namely forward injection, reverse injection and forward and reverse mixed injection. Injection angle was35° for both forward and reverse injection holes. It was reported that at high velocity ratio reverse injection resulted higher and more uniform cooling than forward injection. Moreover, configuration with alternate forward and reverse injection demonstrated improved film cooling effectiveness and maintained film cooling performance from near holes exit to far downstream region.

Experimental studies are not always practical to investigate various aspects and variables of a problem of the domain under study due to their limitations, complexity and cost involvements. Advanced computational fluid dynamics (*CFD*) softwares, on the other hand, are very powerful tools to carry out complex numerical studies and to visualize various fluid flow phenomena though they need to be validated through experimental results of problems of similar kind. To further reduce the complexity involved in full coverage film cooling of practical scenario such as of combustor liner and turbine stator and rotor blades, experimental studies have been mostly conducted on adiabatic flat plates with effusion cooling holes under numerous approximations at scaled boundary conditions.

In summary, there is little data available in literature on full coverage film cooling with combination of both forward and backward injection with holes injecting at two different angles. In companion paper [18] numerical study of full coverage film cooling on an adiabatic flat plate was carried out for a configuration having both forward and backward injection holes called as mix injection and the results of this study, in terms of film cooling effectiveness, was compared with those obtained for film cooling with only forward and only backward injections. In mix injection, rows of film cooling holes inject in alternate backward and forward directions. An array of 20 holes were used with equal hole-to-hole span wise and stream wise pitch values and 30° injection angle for both forward and backward injecting holes. A wide range of velocity ratio, *VR*=0.25 - 5.0 was considered to compare the cooling performance of the three configurations. It was observed that at high velocity ratio, configuration with mix injection not only provided better and more uniform cooling but also supported early transition of effusion film layer from developing stage to developed stage. Present work is the extension of the previous work. In this paper numerical study of full coverage film cooling is attempted for mix injection configuration with holes injecting at two different angles, 15° and 30°. And the film cooling performance of this configuration is compared to that with only 15° and 30° injection holes to explore further the flow physics of mix injection and the influence of the injection angle on film cooling performance. Development of effusion film layer from developing stage to developed stage is also studied for different injection angles.

2. METHODOLOGY

2.1 Computational Model

In this paper film cooling performance of three different cases are studied. Case 1 consists of 15° injection holes, Case 2 consists of 30° injection holes and Case 3 consists of alternate injections at 15° and 30°. The rows of

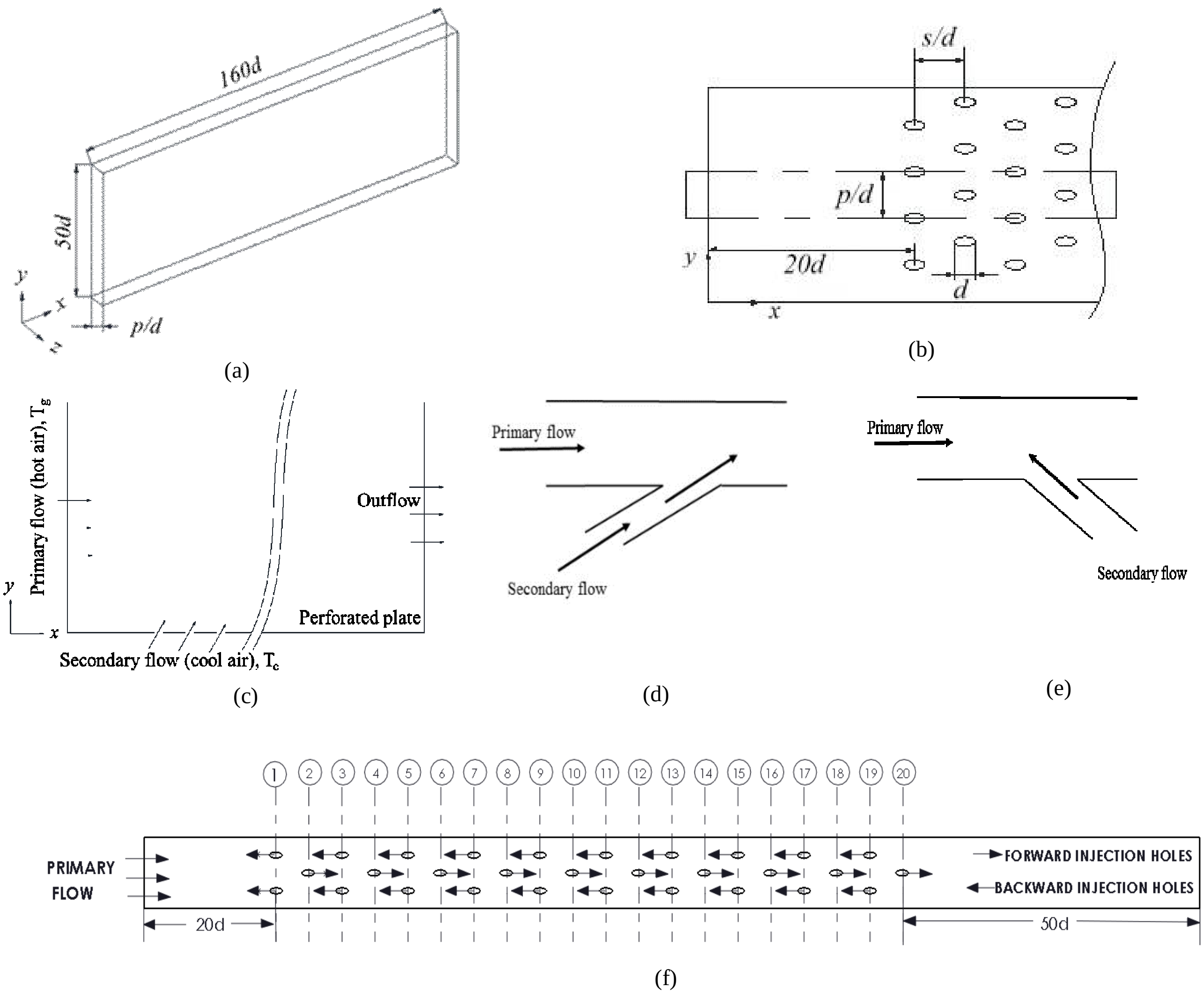


Figure 1. (a) 3D computational domain (b) Details of holes arrangement on the wall [12] (c) Flow schematic (d) Forward injection (e) Backward injection and (f) Mix injection.

cooling jets may inject in forward direction, in backward direction or in alternate backward and forward mix direction as shown in Figs. 1. (d)-(f). For Case1, with forward injection, it is called case 1 with forward injection, for backward injection it is called case 1 with backward injection and for mix injection it is case 1 with mix injection. Similar terminology is used for case 2 and case 3 also. A wide range of velocity ratio of practical importance ranging from *VR*=0.5 to *VR*=2.0 is considered to study film cooling performance of the different cases. The computational domain studied in the present work for all the three cases is shown in Fig. 1. (a). The arrangement of the cooling holes on the wall of the computational domain is shown in Fig. 1 (b). The computational domain consists of an array of discrete holes of 20 rows. The flow schematic is shown in Fig. 1. (c). Working fluid or primary air flows over the perforated plate where it interacts with the jets of cold air or secondary flow which is injected at a certain angle with respect to plate to be cooled. Diameter (*d*) of the cooling holes is 1.0 mm. Hole-to-hole pitch in span wise and stream wise directions are equal (*p/d*=4.9, *s/d*=4.9) and are similar to that used by Scrittore et al. [10] and Has an et al. [12] in their studies. The height (*y*-direction) of the primary inlet is 50*d* which is similar to that used by Yang et al. [11]. Due to the presence of periodic boundary condition the width (*z*-direction) of the computational domain is taken as one span wise hole-to-hole pitch as shown in Fig.1. (b). For all the cases, the first row of cooling holes is at *x=20d*downstream from mainstream inlet and computational domain ends at *x=50d* downstream from the last row of cooling holes.

2.2 Governing Equations

Equations of conservation of mass, momentum, energy and equation of state are solved using the commercial software ANSYS FLUENT 14.5. These equations are well established, and a detailed discussion can be found in Versteeg et al. [19]. Film cooling performance is estimated using a non-dimensional parameter called 'adiabatic film cooling effectiveness (η_{ad})' which is given in the equation below;

$$\eta_{ad} = \frac{T_g - T_{aw}}{T_g - T_c} \quad (1)$$

Where, T_g is hot air temperature, T_{aw} is adiabatic wall temperature and T_c is cool air temperature.

2.3 Numerical Computations

Grid generation for the computational domain is accomplished using Gambit 2.4.6 software. Very fine mesh is generated on adiabatic wall and near the hole exit region to capture the boundary layer accurately. y^+ values less than 1.0 are achieved at all the locations on the adiabatic wall. In this study, Realizable *k-ε* model with enhanced wall treatment is used as the turbulence model [16]. In the computational domain Mach number nowhere exceed 0.3 so the conditions applicable for incompressible ideal gas are used for both primary and secondary flow.

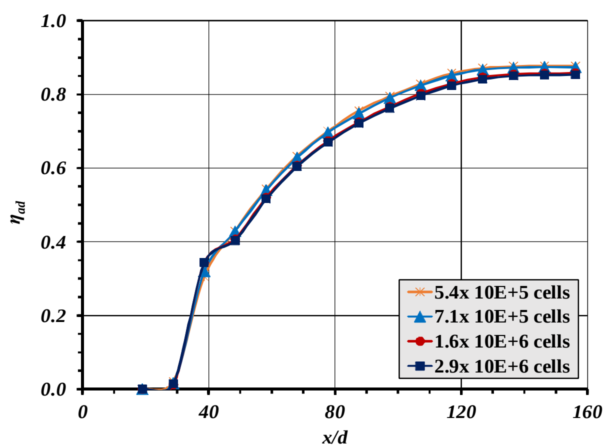


Figure 2: Grid independence study.

Convergence is considered to be achieved when

(a) All the residual values are less than 10^{-4} except energy for which this value is less than 10^{-6} and/or

(b) Average film temperature at the wall remains almost unaltered for at least 100 successive iterations.

Grid independence test is performed at *VR* = 0.5 for case 1 with forward injection and the computational results are shown in Fig. 2. Approximately 1554000 wedge cells are involved in the computation.

2.4 Boundary Conditions

A non-dimensional parameter known as the velocity ratio (*VR*) is defined as;

$$VR = \frac{V_c}{V_g} \quad (2)$$

Where, V_c and V_g are inlet velocity of secondary flow (cool air) and free stream velocity of primary flow (hot air) respectively. Velocity ratio is a measure of strength of coolant jet relative to primary flow. Primary and coolant flow inlets are defined as velocity inlet. Primary flow velocity is kept at, V_g = 50 m/s for the all the calculations whereas, value of V_c depends on the velocity ratio applicable to a case. For all the cases temperature of the primary flow inlet (T_g) is taken as 350K and temperature of coolant flow inlet (T_c) is 300K. A turbulent intensity 0.5% is used for both primary and coolant flow inlets. Turbulence length scale of 3% of height of the primary flow inlet is used for primary flow inlet boundary condition. The flow outlet condition is set as outflow with static pressure at 1atm. Adiabatic no-slip condition is considered for perforated wall. The top and transverse planes are considered as symmetry.

2.5 Validation of Numerical Approach

The approach of the numerical simulation is validated by comparing the results of the numerical simulations for case 1 with forward injection and experimental results of Scrittore et al. [10] at velocity ratio, *VR*=3.2.

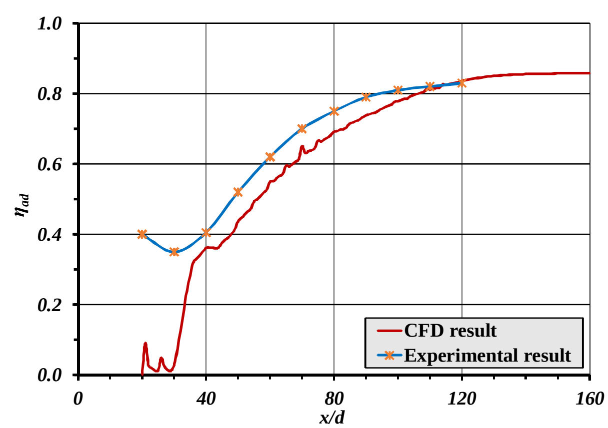


Figure 3: Validation of numerical method.

Fig. 3 shows comparison between the laterally averaged adiabatic film cooling effectiveness distributions along stream wise direction obtained in the numerical simulation and experimental data.

The results of the numerical simulation show reasonably good agreement with the experimental data except for *x/d*<40 which is probably due to the adiabatic approximation of the flat plate as compared to the non-

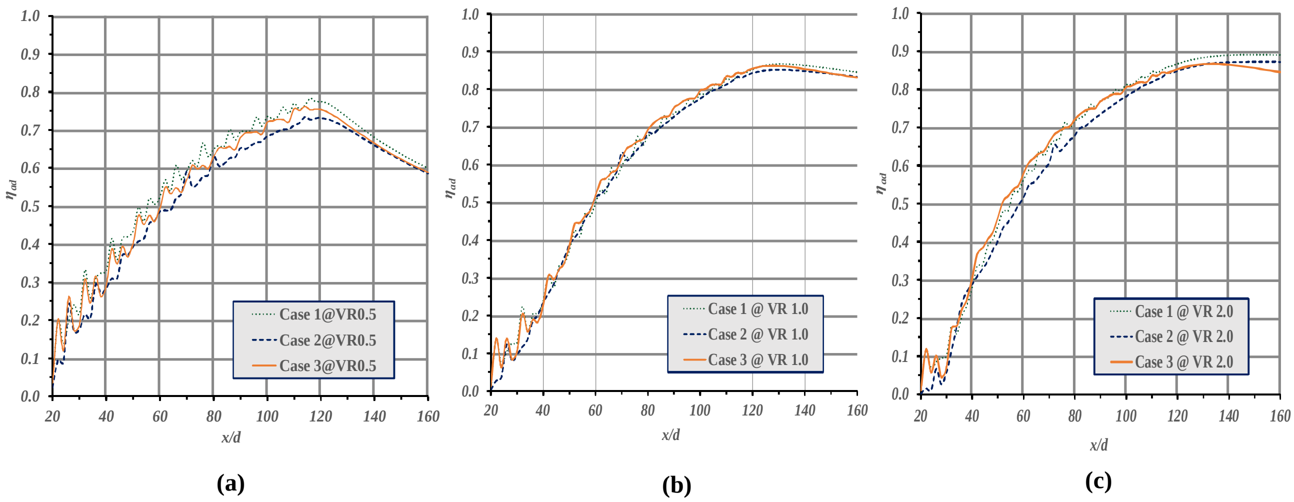


Figure 4: Variation of laterally averaged film cooling effectiveness for Case 1, Case 2 and Case 3, with forward injection at (a) *VR*=0.5 (b) *VR*=1.0 (c) *VR*=2.0.

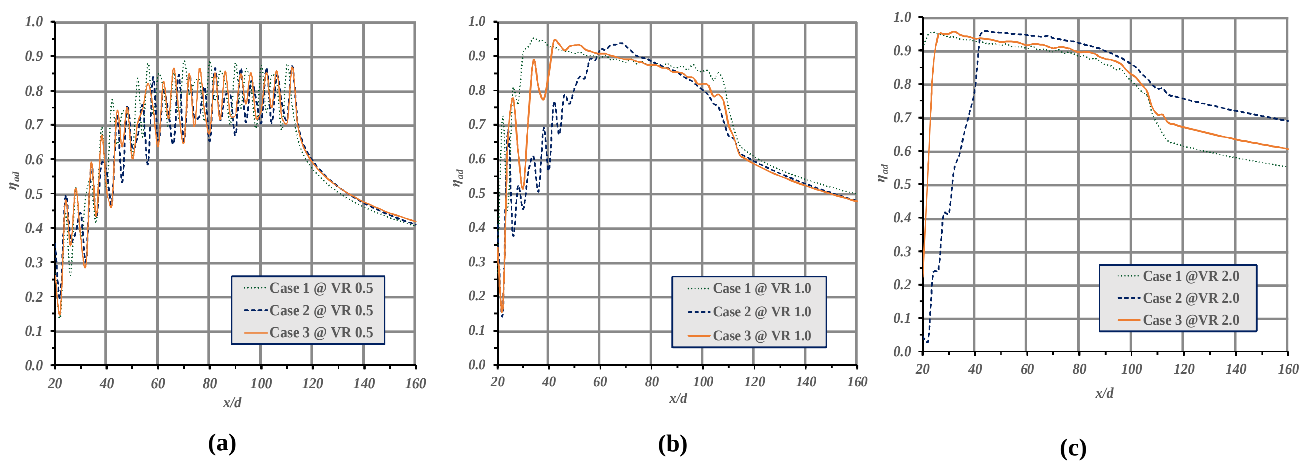


Figure 5: Variation of laterally averaged film cooling effectiveness for Case 1, Case 2 and Case 3, with backward injection at (a) *VR*=0.5 (b) *VR*=1.0 (c) *VR*=2.0.

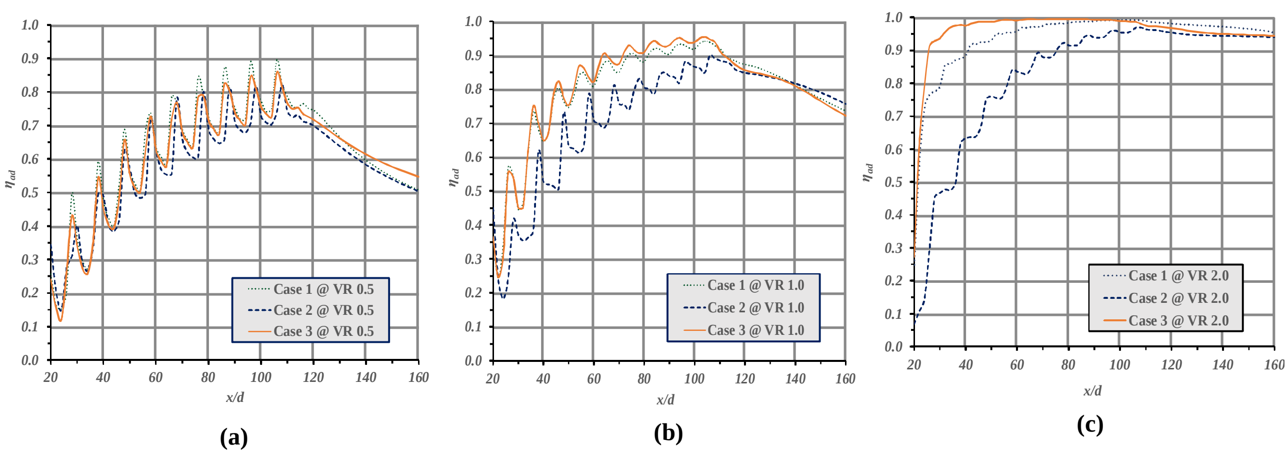


Figure 6: Variation of laterally averaged film cooling effectiveness for Case 1, Case 2 and Case 3, with mix injection at (a) *VR*=0.5 (b) *VR*=1.0 (c) *VR*=2.0.

adiabatic conditions present in the experiments of Scrittore et al. [10].Similar difference in the experimental data and numerical simulation was also observed by Yang et al. [11] and Hasan et al. [12].

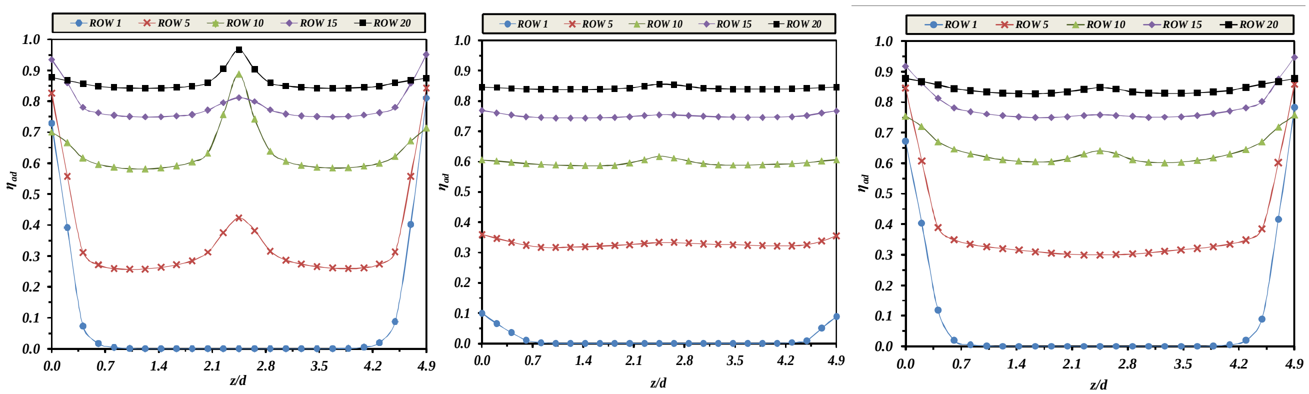
3. RESULTS AND DISCUSSION

3.1 Laterally Averaged Film Cooling Effectiveness

Figs. 4-6 show laterally averaged film cooling effectiveness distributions of the three cases with forward injection, backward injection and mix injection at three different velocity ratios VR=0.5, 1.0 and 2.0. Laterally averaged film cooling effectiveness values are calculated at every 2.0 mm interval along stream wise direction starting from the centreline of the first row of holes. With forward injection holes, the three cases show almost similar trend in the variation of film cooling effectiveness at a particular velocity ratio. Therefore, it can be concluded that for forward injection film cooling performance is poorly influenced by angle of injection for the range under study as shown in Fig. 4.Whereas with backward injection holes and backward and forward mix injection holes film cooling performance of the three configurations are strongly dependent on angle of injection and velocity ratio. For the three cases, high fluctuations in averaged effectiveness values over the perforated region are seen with backward injection at low velocity ratio VR=0.5 and 1.0as shown in Fig. 5. (a) and (b).However, at high velocity ratio, VR=2.0 the three cases with backward injection holes show a sudden rise in film cooling effectiveness near the front few rows of injecting holes as shown in Fig. 5. (c). Film cooling performance with forward injection holes is higher than that with backward injection holes downstream of the perforation region as shown in Fig. 4. &Fig. 5. For mix injection, case 1 and case 3 show almost similar trend of variation in film cooling effectiveness at low velocity ratios, VR=0.5 and 1.0 as shown in Fig. 6. (a)and (b). But at high velocity ratio, VR=2.0, case 3 with mix injection shows highest film cooling effectiveness values among the three cases with mix injection as shown in Fig. 6. (c). Film cooling effectiveness values with mix injection holes are higher than backward injection holes except for few upstream rows. In the range of low velocity ratio (VR=0.5 to 1.0) the effusion film layer never attains developed stage and the cooling effectiveness gradually decreases in the downstream region beyond the perforation. This happens due to the comparatively lower momentum in the secondary flow jet as compared to the primary flow at low velocity ratios. This low momentum in the secondary flow makes it unable to maintain the temperature of effusion film layer beyond the perforation region and it gets heated up in the downstream region due to main stream hot air. But at velocity ratio (VR=2.0), due to high momentum in the secondary flow, the effusion film layer attains developed stage at very early and continued even beyond perforation region. Mix injection cooling presented in this study has an advantage of continuously increasing film cooling effectiveness till the effusion film layer attains developed stage at high velocity ratio, VR= 2.0 which is never seen with backward injection holes.

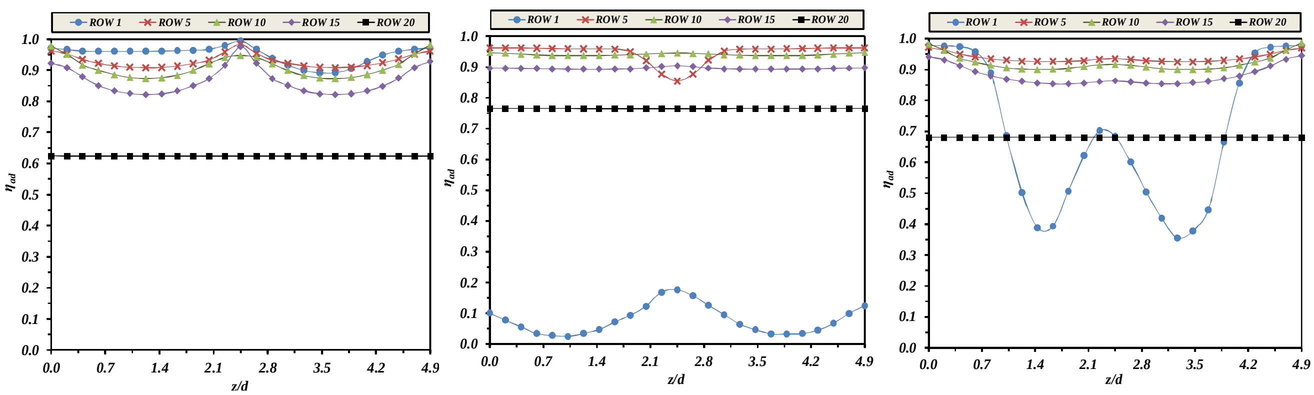
3.2 Laterally Distribution of Film Cooling Effectiveness

Distributions of film cooling effectiveness values along the lateral direction for the three cases at the exits of Row 1, Row 5, Row 10, Row 15 and Row 20 of cooling holes at *VR* = 2.0 are shown in Figs. 7., Fig. 8. and Fig. 9. respectively for forward injection, backward injection and mix injection. For case 1 with the forward injection holes, film cooling effectiveness fluctuates along the lateral direction and this fluctuation is seen over the entire perforated region as shown in Fig. 7 (a). Whereas, for case 2 and case 3 with forward injection, this fluctuation is limited up to the row 10 and row 15 respectively as shown in Figs. 7. (b). - (c). In all the three cases, with forward injection, averaged value of film cooling effectiveness increases along downstream direction. However, with backward injection, lateral variations in film cooling effectiveness are large for case 1 as compared to the other two cases and this variation is more than that with forward injection case as shown in Figs. 8. (a) - (c). But lateral variation in the film cooling effectiveness is not seen in case 1 and case 3 after row 15 and in case 2 after row 5. For the mix injection, case 3 does not show any lateral variation in film cooling effectiveness from row 5 onwards. Whereas, for case 2 film cooling effectiveness along the lateral direction varies up to row 10 for case 3. This variation is limited till row 10. Close examination of the variation of film cooling effectiveness values for the three cases with forward, backward and mix injection shows that for forward injection film cooling effectiveness increases towards downstream direction whereas in the case of backward injection the film cooling effectiveness attains a peak value in the upstream region and its value starts decreasing towards downstream direction. Whereas, the configuration with mix injection holes shows continuous increase in value of laterally averaged film cooling effectiveness towards downstream direction similar to cases with forward injection holes but it attains value highest of the remaining two injections. In mix configuration the laterally averaged value of the film cooling effectiveness becomes constant in the downstream region that shows development of effusion film layer from developing stage. This result shows better lateral spread of the coolant layer for the mix injection as compared to the reverse injection.



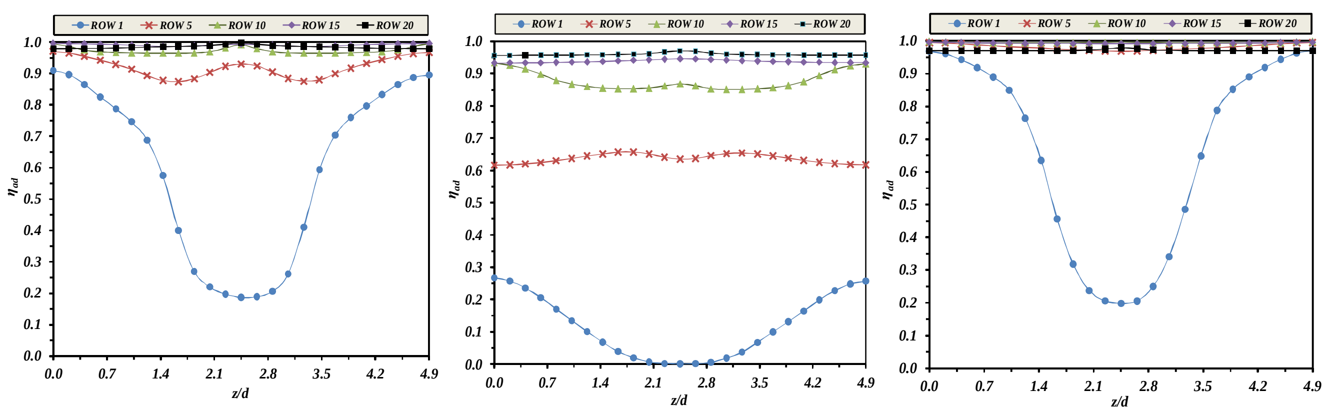
(a) (b) (c)

Figure 7. Lateral distribution of film cooling effectiveness with forward injection at velocity ratio *VR*=2.0 for (a) case 1(b) case 2(c) case 3.



(a) (b) (c)

Figure 8. Lateral distribution of film cooling effectiveness with backward injection at velocity ratio *VR*=2.0 for (a) case 1(b) case 2(c) case 3.



(a) (b) (c)

Figure 9. Lateral distribution of film cooling effectiveness with mix injection at velocity ratio *VR*=2.0 for (a) case 1(b) case 2(c) case 3.

4. CONCLUSION

Numerical study of film cooling on an adiabatic flat plate has been carried out for three cases with two angles of injection. The study shows that at high velocity ratio, mix injection gives better and more uniform cooling than forward and backward injections. Moreover, mix injection with alternate rows of 15° and 30° injection gives higher film cooling effectiveness values than mix injection separately with 15° injection and 30° injection. Angle of injection has least influence on the film cooling performance with forward injection in the range of injection angle studied. Mix injection also demonstrates better lateral coverage of effusion film layer and less variation in film cooling effectiveness in lateral direction. Moreover, mix injection supports early transition of developing effusion film layer to developed stage.

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