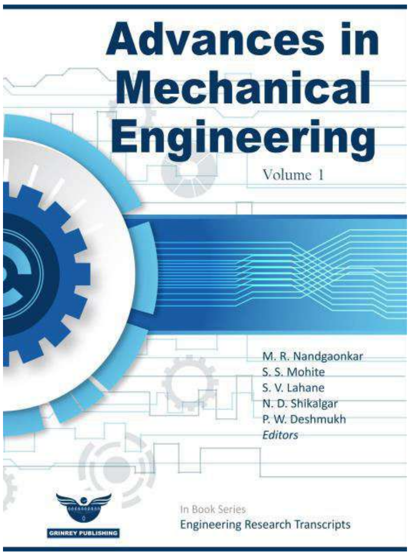

Numerical Analysis of Multi-Zone Effusion Cooling with Super-Long-Diamond Arrangement

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Abstract

The current study employs a 3D numerical analysis on an adiabatic flat plate for full-inclusion film cooling. A super-long-diamond (SLD) arrangement with 5×5×5 holes configuration is used with 30° forward coolant injection at velocity ratios (0.5, 1.5 and, 2.5). The SLD arrangement with 5×5×5 holes configuration has been studied, and a comparison between long-diamond (LD) and SLD arrangement for multi-zone configuration has been made. The aim of the present study is to increase film cooling effectiveness with minimum coolant supply. Results show that the super-long-diamond arrangement with 5×5×5 holes configuration provides better cooling effectiveness than a long-diamond arrangement with 5×5×5 and 6×6×6 holes configuration, which also reduces the number of effusion holes requirement.

1. Introduction

Gas turbines have achieved a better performance in the last few decades. The credit goes to the better effusion cooling techniques that have helped us reach turbine inlet temperature up to 2000K and even more. The experts work day and night to further increase combustor efficiency by reducing the coolant requirement [1]. The present work's main objective is to gain maximum cooling effectiveness with fewer effusion holes.

The holes are arranged in a staggered pattern on the combustor liner's surface to protect from hot combustible gases by forming the developed effusion layer. The coolant supplied from these effusion holes covers the liner's surface by making a coolant layer over it—effusion cooling help in maintaining temperature gradients so that surface remains protected from thermal deformation [2]. Effusion cooling is the most efficient cooling technique among all available cooling techniques in gas turbine engines. The effusion cooling depends on many parameters, such as hole inclination, effusion hole diameter, number of cooling holes, and many more. The main two parameters are coolant injection angle and blowing ratio, which have attracted many designers.

The multi-hole arrangement with staggered pattern provide more cooling than holes arranged in a line [3]. Yang et al. [4] carry out simulations on a multi-hole arrangement by maintaining the perforated percentage constant. The super-long-diamond (SLD) layout with forward injection holes was shown to produce the most cooling compared to the square diamond (SD) and long-diamond (LD) arrangements.

Hasan et al. [5] undertake numerical simulations for multi-zone holes with forward injection holes using an adiabatic perforated plate. The layout with 12×6 holes was determined to be the most suited, providing the best cooling performance at a greater velocity ratio. In their numerical and experimental research, Oguntade et al. [6] discovered that backward injection holes yield superior cooling than forward injection holes. Singh et al. [7] concluded from their experimental and numerical analysis that backward injection holes should be used instead of forward injection holes for improved cooling performance. Sehjn et al. [8-9] used forward, backward, and mixed injection holes in their experimental and numerical analysis and suggested that mixed injection holes should be used rather than only forward and backward injection holes.

Scrittore et al. [10] use a perforated flat plate with 20 rows of effusion holes with the same lateral and longitudinal pitch to conduct their studies. The cooling performance improved as the momentum flux ratio was increased. Mishra et al. [11] investigate the adiabatic perforated flat plate for long-diamond arrangement numerically. At a greater velocity ratio, they discovered that mixed injection holes give the most effective cooling. They also discovered that injecting coolant at a 30° angle provided the highest cooling performance [12]. Prakash et al. [13] perform a numerical simulation for a multi-hole layout on an adiabatic perforated flat plate. The super-long-diamond arrangement, they find, is the best of the three, offering the most effective cooling for the same mass flow rate.

The current research is a continuation of past research [14]. The numerical study of a long-diamond arrangement with two and three-zone holes was undertaken by Prakash et al. [14]. The super-long-diamond arrangement with 5×5×5 holes layout for forward injection holes was investigated in this research at varied velocity ratios (0.5, 1.5, and 2.5). The SLD arrangement with 5×5×5 holes configuration provides better cooling effectiveness than a long-diamond arrangement with 5×5×5 and 6×6×6 holes configuration, which also reduces the number of effusion holes requirement.

2. Methodology

2.1 Computational Model

The perforated plate with 5×5×5 holes configuration for super-long-diamond arrangement is used in the present work, as shown in Fig. 1. The pitches are denoted as P and S for lateral and longitudinal, respectively.

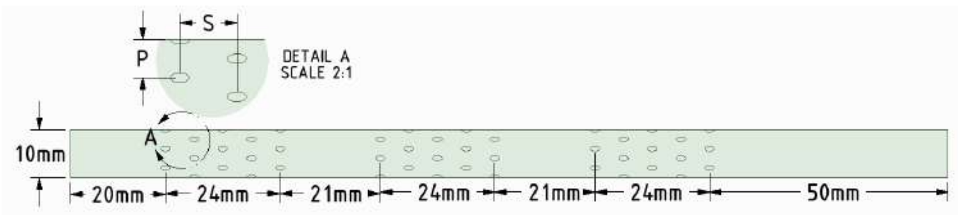


Fig. 1. SLD arrangement on the perforated plate for 5×5×5 configuration [P/d=4, S/d=6]

The perforated plate contains cylindrical holes of diameter (d), 1.0 mm are arranged in a staggered pattern. The 15 rows of holes are used in the present study. The secondary fluid (cool air) and primary fluid (hot air) were taken as working fluid for the numerical analysis. For forward injection holes, the hot fluid flows through the perforated plate surface, and the coolant is provided at a 30° angle to the perforated plate. The computational domain of height equal to 50d (y-direction) and direction of injection holes are shown in Figure 2.

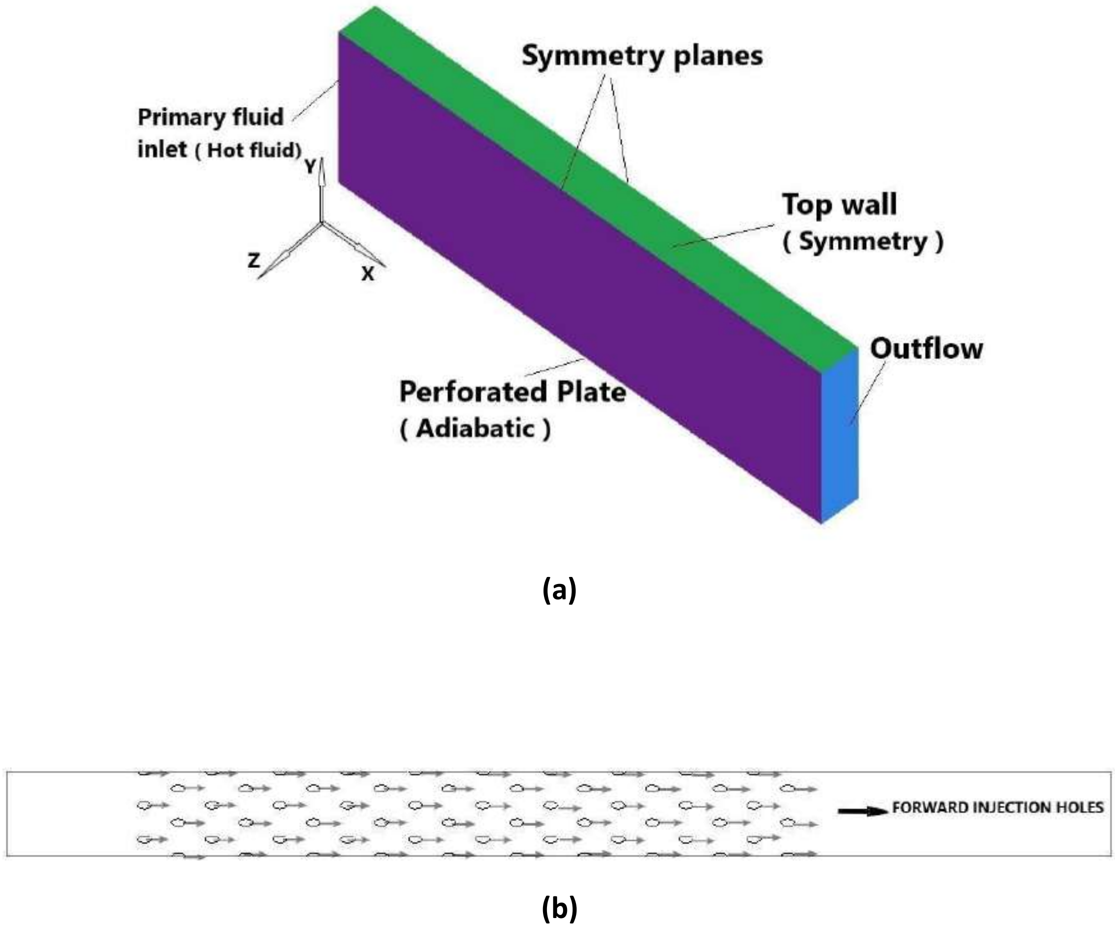


Fig. 2. Computational Domain (a) 3D computational domain, (b) Forward injection holes

2.2 Governing Equations

All of the governing equations in this analysis were solved using the ANSYS Fluent solver. Versteeg et al. [15] discussed these equations in detail in detail. The parameter blowing ratio (M) used in this study is presented by equation 1;

$$M = \frac{\rho_c U_c}{\rho_g U_g} \tag{1}$$

Where

ρ and U *represent* the density and velocity of working fluid and c and g convey coolant and hot fluid, respectively.

According to Yang et al. [4] and Mishra et al. [11], the flow was assumed to be incompressible, and the density ratio was assumed to be unity. As demonstrated in equation 2, equation 1 is reduced to merely velocity ratio (VR).

$$M = \frac{U_c}{U_g} \tag{2}$$

The adiabatic film cooling effectiveness (η_{ad}) is calculated by equation 3;

$$\eta_{ad} = \frac{T_g - T_{ad}}{T_g - T_c} \qquad (3)$$

Where

T_g , T_{ad} and T_c Represent the temperature for hot fluid, perforated wall, and coolant fluid, respectively.

2.3 Boundary conditions

The 5×5×5 holes configuration with the super-long-diamond arrangement is studied with varying velocity ratios (0.5 to 2.5). In this study, the primary flow velocity is 50 m/s, and secondary flow velocity is calculated for various velocity ratios. The secondary flow is issued at a 30° angle for forward injection holes. An adiabatic no-slip condition is imposed on the perforated wall of the 3D domain. At the domain's outflow, atmospheric pressure is employed. According to Yang et al. [4] and Mishra et al. [11], the transverse planes and top wall are treated as symmetry to reduce domain dimensions, which aids in rapid computing due to fewer cells. The Reynolds number (Re) before the hole for a primary flow of 50 m/s is 40531.77. The remaining boundary criteria are listed in Table 1.

Table 1. Boundary conditions for primary and secondary flow

	Velocity ratio	**Velocity inlet (m/s)**	**Temperature (K)**	**Turbulence Intensity (%)**	**Turbulence length (m)**	**Hydraulic dia (m)**
Primary flow	--------------	50	350	0.5	0.0015	-------------
Secondary flow	0.5	25	300	0.5	---------------	0.001
	1.5	75				
	2.5	125				

2.4 Numerical computations

ICEM CFD developed the non-uniform structured mesh for the whole computational domain. The y+ value was kept below 1.0 throughout the perforated plate to capture the boundary layer effect. A realisable k-epsilon turbulence model was used, as suggested by Sinha et al. [16] and El-Gabry et al. [17]. The residual values were used for convergence in the present study are 10^{-6}, 10^{-4} and 10^{-5} for energy, continuity, and all other variables, respectively.

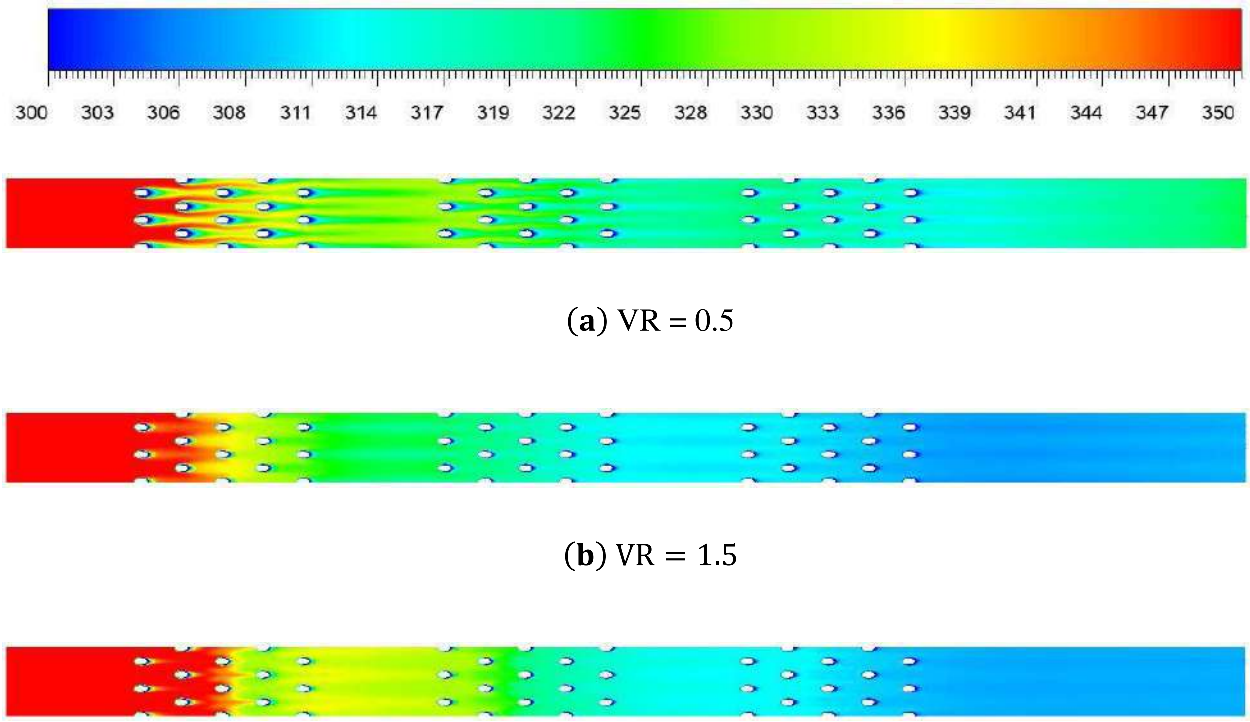
2.5 Grid Independence Study and Validation of Numerical Approach

The grid independence analysis was carried out with forward injection holes for a velocity ratio of 0.5. Around 3.2 million structured cells are used in the numerical analysis. The experimental data of Scrittore et al. [10] at a velocity ratio of 3.2 was used to validate the current computational research. The companion paper [13] has more information on the grid independence investigation and the numerical approach's validation.

3 Results and Discussion

3.1 Wall temperature profile

Computational analyses were carried out for forward injection holes at velocity ratios (0.5, 1.5, and 2.5) for 5×5×5 configuration with the SLD arrangement. The temperature contours are plotted on the adiabatic perforated plate for different velocity ratios, as shown in Figure 3.



(**a**) VR = 0.5

(**b**) VR = 1.5

(**c**) VR = 2.5

Fig. 3. Adiabatic wall temperature distributions for 5×5×5 configuration with SLD arrangement at **(a)** VR =0.5, **(b)** VR = 1.5 and, **(c)** VR = 2.5

The 5×5×5 holes configuration with SLD arrangement provides uniform cooling than the long-diamond arrangement. The developed effusion layer was achieved at velocity ratio 1.5 on the adiabatic perforated plate. The lowest temperature was found with the SLD arrangement for 5×5×5 holes configuration. The flow is not created at a low-velocity ratio due to the slow movement of coolant flow, as seen in Figure 3. (a). The secondary flow is also mixing with the primary flow at a velocity ratio of 2.5, and the flow is not fully developed. But, for velocity ratio 1.5, flow is fully developed due to proper spreading of coolant flow. The profile of temperature contours from Figure 3 concludes that the SLD arrangement at velocity ratio 1.5 maintains the smooth flow of secondary flow over the perforated plate and achieves an early developed effusion layer.

3.2 Streamwise variation in film cooling effectiveness

The laterally averaged film cooling effectiveness is computed for the SLD arrangement with forward injection holes along the longitudinal direction for velocity ratios (0.5, 1.5, and 2.5).

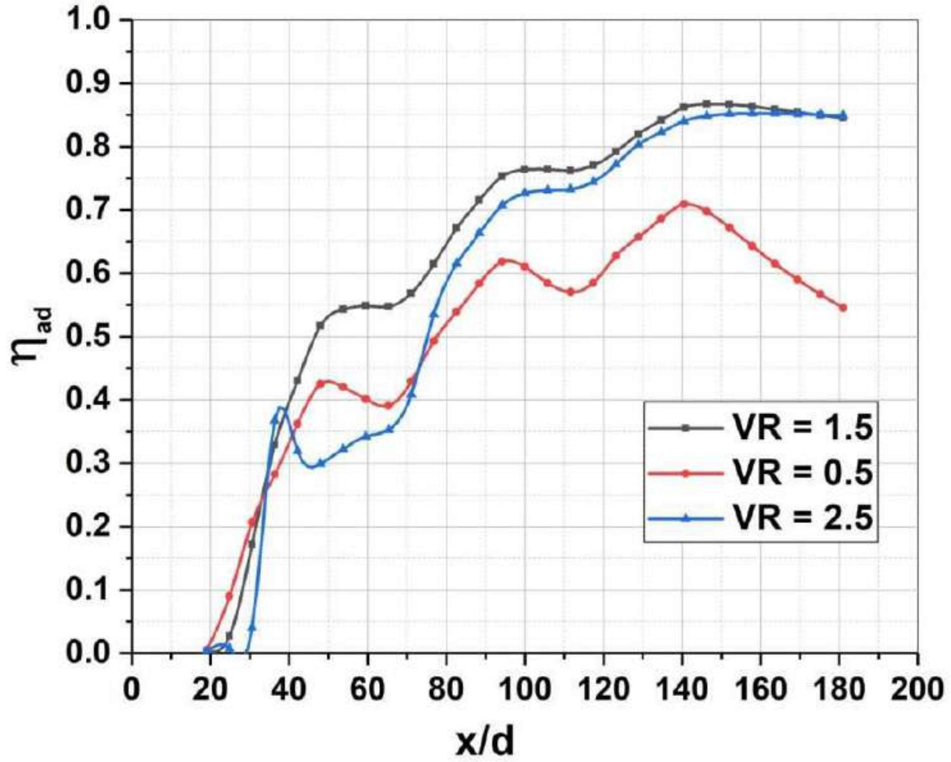


Fig. 4. Laterally averaged adiabatic film cooling effectiveness with SLD arrangement for 5×5×5 holes configuration at VR = 0.5, 1.5 & 2.5

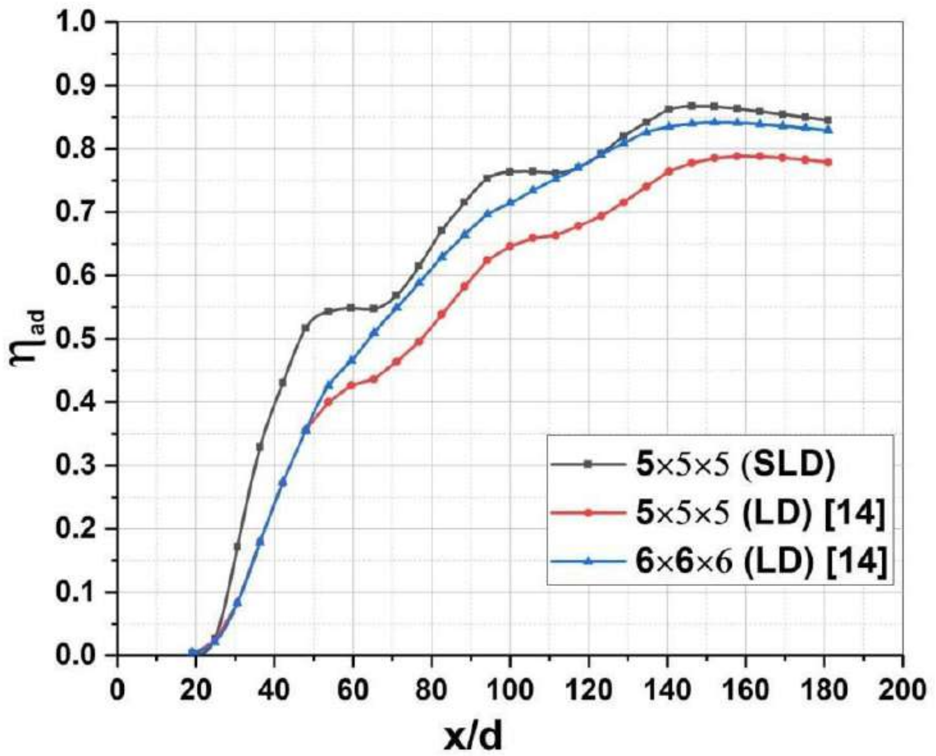
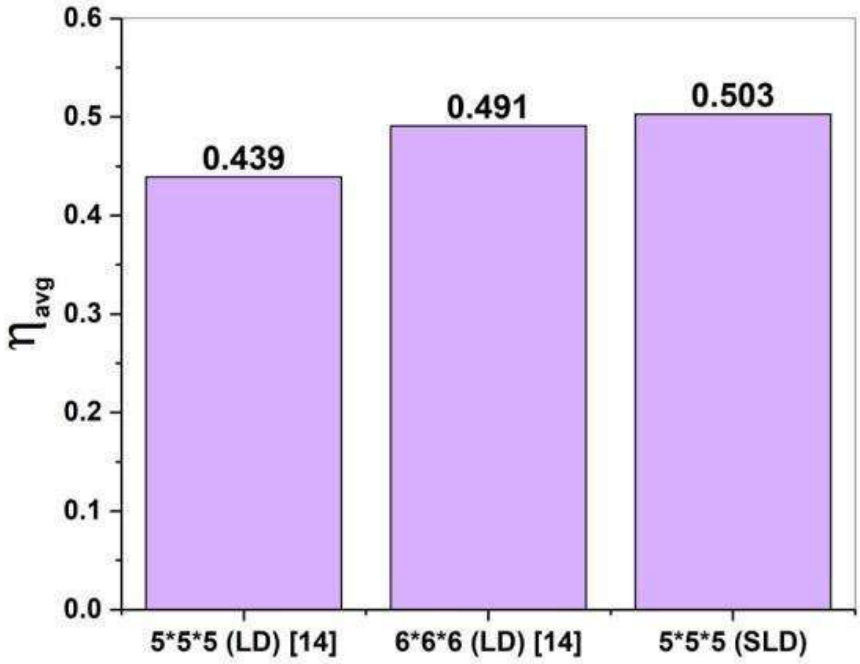
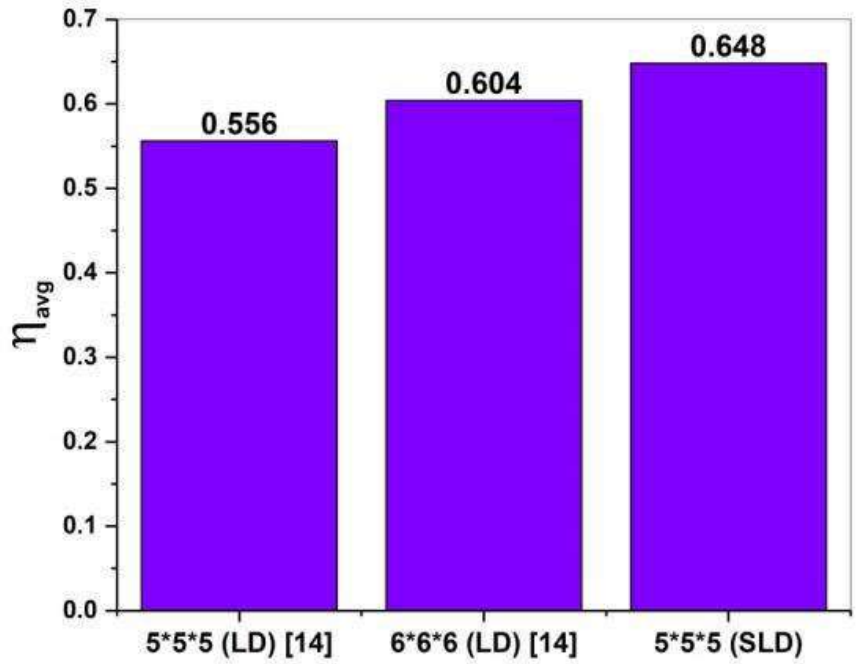


Fig. 5. comparison of laterally averaged adiabatic film cooling effectiveness between LD and SLD arrangement at VR =1.5



(a)



(b)

Fig. 6. Comparison of the average of laterally averaged adiabatic film cooling effectiveness at **(a)** VR =0.5, **(b)** VR = 1.5

As demonstrated in Figure 4, the effectiveness of laterally averaged adiabatic film cooling increased with increasing velocity ratio up to a certain point before diminishing due to secondary flow penetration into the primary flow. The cooling effectiveness for 5×5×5 holes configuration with SLD arrangement will provide the highest cooling effectiveness at velocity ratio 1.5. With the SLD arrangement, the maximum cooling effect is almost 0.7, 0.87, and 0.85 at velocity ratios (0.5, 1.5, and 2.5), respectively. Figure 4 shows that the 5×5×5 structure with SLD arrangement at velocity ratio 1.5 provides the most effective film cooling.

A comparison was made between LD and SLD arrangement at velocity ratio 1.5 from Figure 5. It was seen that the 5×5×5 holes configuration with SLD arrangement provides better cooling compared to 5×5×5 and 6×6×6 holes configuration with a LD arrangement. Even with the fewer effusion holes, the 5×5×5 layout with the SLD arrangement was determined to be a far superior choice for effusion cooling than the LD arrangement.

Similarly, Figure 6 shows a comparison of LD and SLD layouts. At a velocity ratio of 0.5, the SLD arrangement boosted film cooling effectiveness by 14.57% and 2.44%, respectively, compared to the LD configuration. At velocity ratio 1.5, film cooling effectiveness increased by 16.54% and 7.28% for 5×5×5 with SLD arrangement compared to 5×5×5 and 6×6×6 with the LD arrangement, respectively. Because there are fewer effusion holes on the perforated plate, the 5×5×5 holes configuration with a SLD pattern minimizes the coolant requirement.

4 Conclusions

The film cooling effect on super-long-diamond arrangement with 5×5×5 holes configuration consisting of forward injection holes at varied velocity ratios (0.5, 1.5, and 2.5) was investigated in this study, and the results are discussed below;

1. The temperature distribution for different velocity ratio manifests that flow was fully developed at velocity ratio 1.5 and shows early signs of effusion layer, which reduces the perforated wall temperature.
2. The 5×5×5 holes configuration with SLD design delivers the maximum film cooling effectiveness at velocity ratio 1.5 compared to 5×5×5 and 6×6×6 holes configuration with a long-diamond arrangement.
3. Film cooling effectiveness increased by 14.57% and 16.54% for the 5×5×5 holes configuration with super-long-diamond arrangement at velocity ratio 0.5 and 1.5 respectively compared to 5×5×5 holes configuration with long-diamond arrangement with the same mass flow rate. The 5×5×5 holes configuration with the SLD arrangement also provides 2.44% and 7.28% more cooling effect at velocity ratio 0.5 and 1.5, respectively, than 6×6×6 holes configuration with the long-diamond arrangement, lessening the cooling air demand.
4. When compared to a long-diamond arrangement, the 5×5×5 holes layout with super-long-diamond arrangement provides optimum cooling performance due to optimal lateral and longitudinal pitches, which aid in proper secondary flow dispersion. The maximum cooling effectiveness is achieved by 5×5×5 with the super-long-diamond arrangement are almost 0.7, 0.87 and, 0.85 at velocity ratios (0.5, 1.5, and 2.5), respectively.
5. The study recommends the use of super-long-diamond arrangement with all the configurations in place of long-diamond arrangement.

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