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Numerical Investigation of the Effect of Coolant Injection Angle on the Pulsed Film Cooling Effectiveness of Square Wave Flow on Flat Plate

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ABSTRACT: The effect of the angle of injection on the film cooling effectiveness with square wave pulsation is investigated at various frequencies. Four angles of injection are selected at 20, 25, 30 and 35 degrees. Film cooling is used to cool turbine blades and extend the life of blade. The pulsed flow is investigated at three frequencies of 2, 50 and 500 Hz. Finite volume method is used to solve the flow governing equations. The shear stress transport k-ω model is used to model the turbulence. The obtained results showed that the injection angle of 20 to 25 degrees had the most film cooling effectiveness for all frequencies. In higher frequency, 500 Hz, it is observed an increase in the effectiveness of the film cooling in close distances after the injection holes. At far distances, the lower frequency, 2 Hz, produces the most effectiveness. The largest difference in centerline effectiveness is achieved at 500 Hz for hole angles of 20 to 35 degrees with a value of 64.3%. This value is 98.9% for lateral effectiveness. As the frequency increases, the cooling mass flow interruptions are reduced, and as a result, the instantaneous effectiveness shows a slower variation than the lower frequencies. The blowing ratio of 0.5 had the most value in comparison with the blowing ratio of 0.75 and 1 in all angles and frequencies. The maximum difference in effectiveness is 187.4% for blowing ratio of 0.5, in comparison with the other two blowing ratios.

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Frequency

1- Introduction

As the need for higher overall efficiency and higher output power is needed, modern gas turbine systems are needed to operate at higher turbine input temperatures, which are now beyond the acceptable level of materials. Therefore, effective cooling methods should be used in turbine blades to maintain heat stress. Film cooling are applied to almost all external surfaces of airfoils exposed to hot combustion [1]. Over the last decades, significant studies have been done to understand the basic physics of the film cooling flow. Previous studies have shown that film cooling is affected by several factors such as blow ratio, hole shape, position and direction of injection [2]. Film cooling performance is affected by mainstream characteristics such as pressure gradient, secondary flow and turbulence intensity [3]. The use of pulsing jets with the aim of film cooling can lead to improved efficiency, and therefore the input temperature to the turbine is higher without affecting the blade's life [4]. In many industrial applications, pulsing flow occurs due to moving parts such as pumps or turbines, or by vibrations or fluctuations in flow [5]. Coultard et al. [6] experimentally investigated a row of film cooling in cross flow on a flat plate. Jets angle was 35 degrees to the surface in the direction of flow. Blowing ratios ranged from 0.25 to 1.5, duty cycles ranged from 0.25 to 0.75, and Strouhal numbers ranged from 0.0119 to 0.1905 were considered. The highest film cooling effectiveness was obtained in the blowing ratio of 0.5 with steady blowing. With increasing in blowing ratio, the jet effectiveness was reduced. The overall result was that the pulsation for the geometry and the properties of the current study did not have any beneficial effect on the film cooling. Muldoon and Acharya [7] examined the pulse film cooling with direct numerical simulation model. The geometry included a cylindrical jet with slope of 35 degrees relative to the mainstream. At frequency higher than 0.5 and blowing ratio of 1.5, the improvement of the film cooling effectiveness was achieved in blowing ratio 1.5 due to reduced jumping compared to steady sample.

In researchers' investigations, one of the two parameters of coolant injection angle and frequency of pulsation is considered constant. So, in this article, the effect of simultaneous changing of injection angle and coolant flow frequency is studied. In previous by researchs, the frequencies are usually fixed or the entire range of low, middle, and high frequencies is not covered. In this paper, the effect of the flow with low frequency range (less than 10 Hz), middle (between 10 and 100 Hz) and high (more than 100 Hz) on the film cooling effectiveness is investigated.

2- Methodology

Continuity, momentum and energy equation for computational domain are solved.

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

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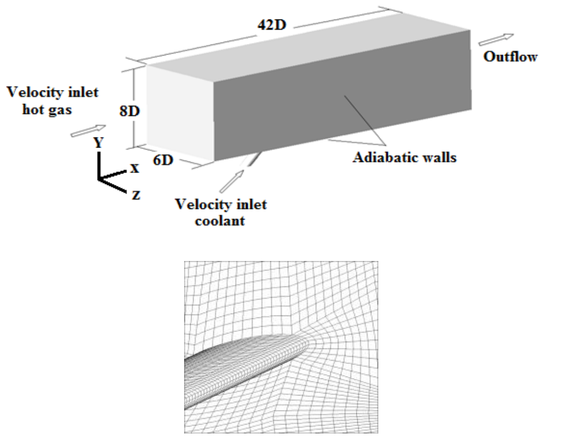
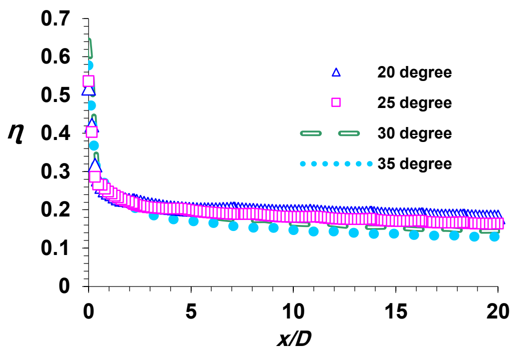
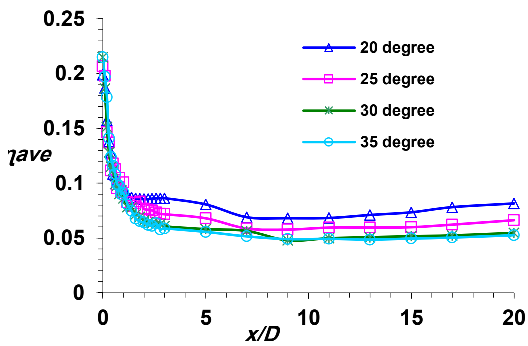


Fig. 1. The computational area, boundary conditions and mesh around the injection hole



(a)



(b)

Fig. 2. Comparison of the pulse film cooling effectiveness at different angles and 50 Hz (a): centerline (b): averaged laterally

$$\frac{DU_i}{Dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\upsilon \frac{\partial U_i}{\partial x_j} - \overline{u_i u_j}\right) \quad (2)$$

$$\rho U_i \frac{\partial \overline{T}}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{k}{c_p}\frac{\partial \overline{T}}{\partial x_i} - \rho \overline{u_i T}\right) \quad (3)$$

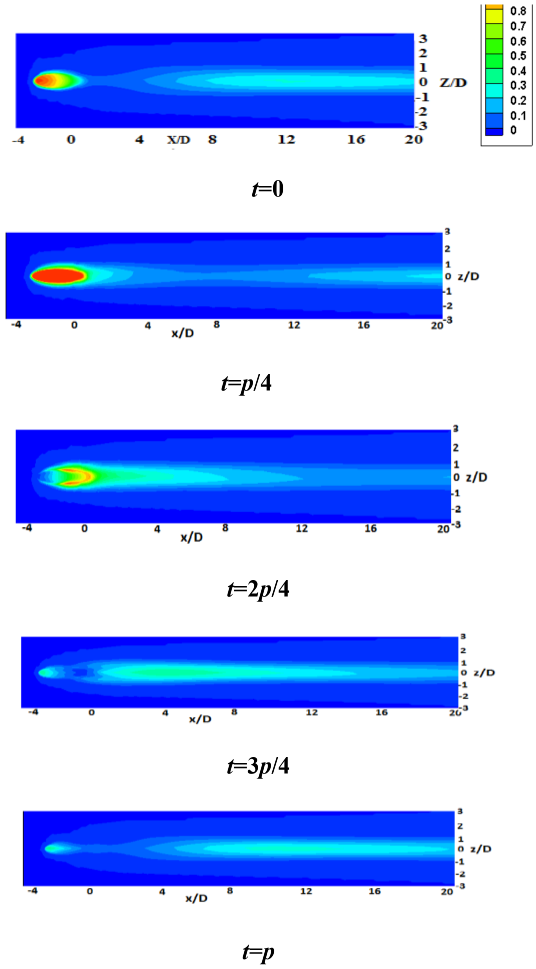


Fig. 3. Distribution of effectiveness for frequency of 50Hz

Shear Stress Transport (SST) k-ω model is used for modeling turbulence. The geometry of the problem consists of four injection holes of 5 mm in diameter and L/D=6, and the injection angles of 20, 25, 30 and 35 degrees. Structured hexahedral mesh is used to geometry grid. Fig. 1 shows the problem geometry including the computational area, boundary conditions and grid of around the injection hole with angle of 25 degrees.

For main stream, velocity was 10 m/s. Main flow temperature was 353.15 K and coolant flow temperature was 303.15 K. The turbulence intensity was considered for both mainstream and coolant flow 3.6%. Coolant flow frequencies was 2, 50 and 500Hz.

3- Results and Discussion

Fig. 2-a illustrates the comparison of the centerline film cooling effectiveness and Fig. 2-b shows the lateral film cooling efficiency for frequency of 50 Hz at various angles. By increasing the distance from injection hole, mixing the coolant with hot air around the plate reduces centerline film cooling effectiveness. Fig. 3 shows the effectiveness distribution in downstream of injection hole at different steps of period of square wave frequency of 50Hz.

Due to the non-uniform distribution of velocity due to pulsation, the cooling flow has high local momentum at outlet of up hole. This phenomenon increases coolant penetration to mainstream, causing coolant separation from cooling surface and reduces the film cooling performance.

4- Conclusions

The effect of injection angle on film cooling effectiveness with square pulsation. Results show that the injection angle between 20 and 25 degrees in three frequencies studied had the most effective central and lateral film cooling. As the frequency increases, the slope of decreasing the film cooling effectiveness increased. The blowing ratio of 0.5 was in comparison with blowing ratios of 0.75 and 1 in all angles and frequencies, had the most effective film cooling performance.

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