

Numerical simulation of Gas Turbine Blade Cooling

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Abstract- This study is a numerical investigation of the effect of hole inclination angle and blowing ratio on film cooling effectiveness of elliptical fixed blade surface. The study was conducted on, (I-R MT250) gas turbine data, with 0.7 mm hole diameter, hole injection angles (from 300 to 900) with the horizontal and blowing ratio (from 0.3 to 1.3). Commercial software Comsol multi physics, with use of finite element method, is used for solving a set of RANS equations and (K- ω) turbulence model also is used. The velocity of hot gases is remaining constant during the investigation, but the coolant velocity was varied on the blowing ratio variation. The hot gases flow is inclined by 150 with horizontal at coolant exit. During the study the effect of film cooling layer and mixed coolant-hot gas on reducing the heat transfer between blade surface and main stream was studied. At low and moderate blowing ratios, the results showed an increase in effectiveness, when hole inclination angles increased (from 300 to 600). At higher blowing ratio and an increase in inclination angle more than 600, leads to drop film cooling effectiveness down. Maximum film cooling effectiveness achieved at inclination angle 600 with horizontal, and minimum film cooling effectiveness at 900 with the horizontal.

Key words- Film cooling effectiveness, Inclination angle, blowing ratio, gas turbine, stator blade, cfd.

1-Introduction

In propellant industry especially rockets and gas turbines, some parts are exposed to high temperature, the gas turbine main parts are shown in the figure (1). This high temperature affects parts life time by increasing the rate of corrosion, creep and shape deformation. It is also clear that, the gas turbine efficiency depends on the gas inlet temperature which is limited by the melting points of the turbine materials. So, cooling techniques should be employed to overcome these problems.

For gas turbine, there are many cooling techniques either internal or external. Many investigations were performed in order to reach the optimum cooling of the turbine components. One of the most effective techniques is the film cooling which is widely employed to maintain hot parts temperatures within acceptable range [17]. Film cooling is achieved by injecting a relatively cold air, bled from air compressor, through drilled holes on the blade surface. This injection creates an insulating surface between hot gases and airfoil materials [7].

In order to understand the film cooling behavior and the influence of different operating conditions, many investigations had been performed.

In last decades, many experimental and numerical studies of film cooling were performed as following:

Acharya and Leedom [1] investigated numerically the effects of plenum inflow orientation on film cooling, by large eddy simulation. Three in flow orientations in to the plenum were studied. These orientations were vertically, parallel to and perpendicular to the main stream flow, were investigated. The hole's inclination angle of 35° , fluids density ratio of 2, and blowing ratios from 0.5 to 2.0 were used. The results showed that the longer delivery holes ($L/d = 3.5$) had higher cooling effectiveness except in vicinity of the coolant hole. The flow orientation in to the plenum had a significant effect on cooling effectiveness and on flow behavior in the delivery tube and downstream of the hole. The perpendicular plenum inflow showed the lowest cooling effectiveness, while the parallel plenum flow orientation had the highest cooling effectiveness and discharge coefficients.

Aziz and Jubran [2] Investigated numerically the film cooling stream-wise injection holes with various small hole length-diameter ratios, using a standard k- ϵ turbulence model with wall function. The results showed that extending the computational domain into the plenum supply of the injection holes improved the film cooling effectiveness especially at low blowing ratios. Also, results pointed out that the film cooling reduces as the hole L/D ratio decreases.

Cherrared [3] investigated numerically a 3D model of the CFM56-7B engine blade stator using CFX 5.7.1 simulation software. The effect of two rows of jets on the cooling effectiveness at blowing ratio of 0.5 and inclination angle of 85° and orientation angle of 35° . the results showed that the two rows of holes had a small effect on the blade cooling due to the existence of two vortices in different directions. These vortices

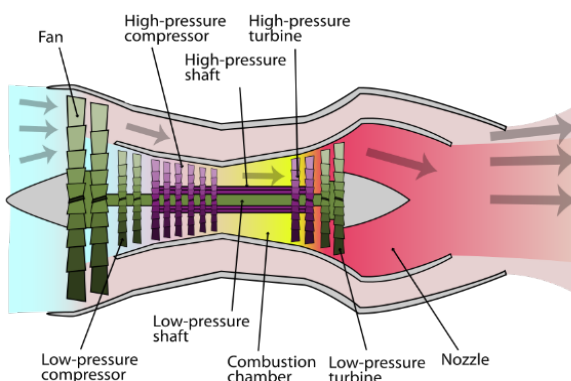


Fig. 1 Turbine Engine main [6]

transported the hot gas into the film cooling layer which degraded the protective wall.

Dittmar et al. [5] studied the film cooling performance in terms of the adiabatic film cooling effectiveness and the heat transfer coefficient of two different injection hole configurations. They used a single row of fan shaped holes and a double row of cylindrical holes in staggered arrangement. Study showed that the two different injection configuration had similar performance until medium blowing ratios 0.75. At higher blowing ratios, the fan shaped holes showed superior effectiveness in a region up to a stream wise distance of $s/d = 30$.

Jung and Hennecke [8] Studied experimentally the effect of curvature shape of gas turbine blade on film cooling effectiveness, with two staggered rows of injection holes by using a mass transfer technique. Additionally, measurements on a flat plate were made for comparison. At low and moderate blowing ratio the effectiveness was enhanced on convex and reduced on concave curved surfaces compared to results obtained from the flat surface. At high blowing ratio the effectiveness was not greatly influenced by surface curvature. The effect of curvature was found to be negligible between the two rows and reduced downstream of the second row compared to results described in the literature for single row injection.

Prasad et al. [11] studied numerically the effect of injection angle on film cooling. They used 3D domain and cylindrical holes with streamwise angles of $(30^\circ, 60^\circ, \text{ and } 90^\circ)$ and blowing ratios ranging from 0.33 to 1.67. Results showed that maximum cooling effectiveness occurred at stream wise injection angle of 30° at blowing ratio of 0.33 due to the closeness of the coolant to the wall surface. They declared also that, by increasing the blowing ratio more than 0.33, film cooling effectiveness decreased.

1.2 Aim of the Present Study

The present study, is an investigation of the film cooling and heat transfer behavior presented for an elliptic stator blade of the gas turbine. The investigation is conducted at different inclination angles and blowing ratios to determine the best inclination angle and blowing ratio that optimize the film cooling effectiveness.

2- Problem Description

2.1 Model Description

Figure (2) shows the 2D domain with one injection hole. The blade elliptical surface is 67 mm long and 2 mm thickness. The hot gases flow through a channel of 21.5 mm width with a mean stream angle of 15° with horizontal at hole exit. The coolant injected into the main stream of the hot gases at different blowing ratios (0.3-1.3) and different inclination angles (30° - 90°) through a hole of 0.7 mm diameter.

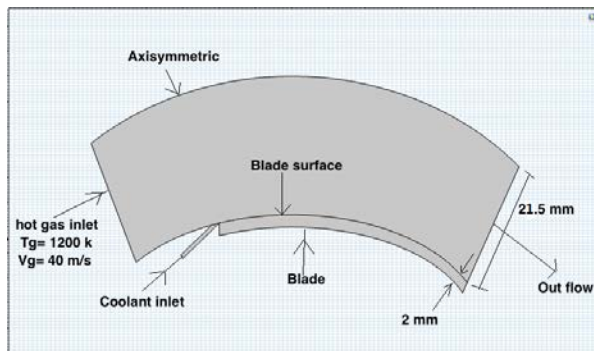


Fig. 2 sketch of stator blade model

2.2 Governing Equations

A commercial software package Comsol Multiphysics software 5.2 [4] is used for solving the conservation of mass, momentum and energy equations and the (K- ω) module for turbulence simulation [15]. The flow is assumed 2D, steady state, and incompressible. The model governing equations are as follows: -

1- Continuity equation

$$\frac{\partial(\rho u_j)}{\partial x_j} = 0 \quad (1)$$

2- Momentum equations

$$\frac{\partial}{\partial x_j} [\rho u_j u_i] = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \frac{\partial u_i}{\partial x_j} \right] - \frac{\partial u'_i u'_j}{\partial x_j} + \rho g_{x_i} \quad (2)$$

Where

μ is dynamic viscosity of fluid, and

$\overline{u'_i u'_j}$ is the turbulence Reynolads stress

3- Energy equation

$$\frac{\partial(\rho u_j T)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\Gamma_e \frac{\partial T}{\partial x_j} \right] + S_T \quad (3)$$

Where:

Γ_e is effective diffusion factor, and S_T is source term. $\text{Kg. } ^\circ\text{C/m}^3 \cdot \text{s}$

K- ω turbulent equations

1- Kinematic eddy viscosity

$$\nu_T = \frac{\kappa}{\omega} \quad (5)$$

2- Turbulence Kinetic Energy

3- For specific dissipation rate of k

$$\frac{\partial(u_j \omega)}{\partial x_j} = \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[\left\{ \mu + \frac{\mu_t}{\sigma_\omega} \right\} \frac{\partial \omega}{\partial x_j} \right] \quad (7)$$

3- Research Methods

3.1 Numerical Methods

The two dimensional RNAS equations are analyzed by the commercial software COMSOL MULTIPHYSICS with the finite element control method. The (K- ω) model is used for medaling the turbulence flow. The Co_2 is used as hot gas and air as coolant. Iron as used for blade surface.

3.2 Boundary Conditions

The main stream velocity, V_g , is considered to 40 m/s and remains constant in all simulation runs and inlet hot gases temperature, T_g , is 1200 K, inlet hot gases, P_g , pressure is 3 bar, while the outlet boundary condition is set to be out flow. The density of CO_2 , ρ_g , is taken as 1.98 kg/m^3 . The blowing ratios considered in his study are 0.3, 0.8, 1, 1.3. This blowing ratio is defined as following:

$$Br = \frac{\rho_c}{\rho_g} * \frac{V_c}{V_g} \quad (4)$$

Where:

V_c : coolant velocity

ρ_c : coolant density

V_g : hot gas velocity

ρ_g : hot gas density

Coolant velocity based on the predetermined (Br)s, the coolant velocity, V_c , takes the values 19.4, 51.72, 64.65 and 84.05 m/s. inlet coolant temperature and pressure are 650 K and 4 bar respectively. Hole exit pressure of was set to be 4 bar and density is 1.225 kg/m^3 . The data is taken from gas turbine catalogue model (I-R MT250), [9].

3.3 Mesh Generation

The commercial software package, Comsol Multiphysics, is used to generate the mesh structure of the problem domain by applying the finite element technique. The whole domain is divided in to three regions, blade surface, coolant and hot stream gas. Around the blade surface and coolant exit number of cells is set to be finer than other regions due to the high gradient of the fluids properties. Many mesh structures are performed to reach the optimum one which gives acceptable accuracy and minimum computing time. The selected mesh consists of 248397 cells.

4-Result and Discussions

In this study the investigation takes into consideration the following two points: -

- 1-The effect of inclination angle and blowing ratio on the film cooling effectiveness.
- 2- The pressure drop due to the injection of coolant fluid.

4.1 Heat Transfer

4.1.1 Temperature distribution along blade surface

Figure (3) describes the variation of the mean temperature along the blade surface at different blowing ratios. It uncovers that at low blowing ratio ($Br < 0.8$) the amount of injected coolant is insufficient to reduce heat transfer between the hot stream and blade surface, which records the maximum blade surface temperature for all inclination angles. The thickness of film cooling layer and mixture in the vicinity of jet exit increases as inclination angle from 30° to 60° increases. The temperature of the blade surface decrease with increasing the inclination angle. for inclination angles more than 60° the mean blade surface temperature increases for all blowing ratios.

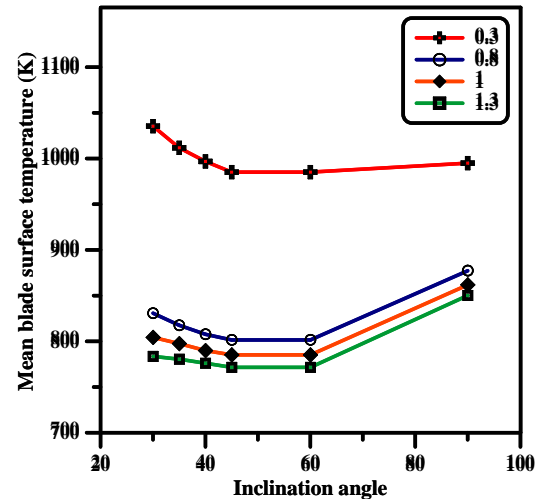


Fig. 3 Mean temperature distribution along blade surface at different inclination angles and blowing ratios

4.1.2 Mean outlet temperature difference

Figure (4) shows the relation between temperature difference (between inlet and outlet) of hot gas. At different inclination angles and various blowing ratios. It's clear that by increasing the blowing the blowing ratio the out let temperature decreases for all inclination angles. While the inclination angles have no effect on the out let temperature except for inclination angle of 90° which gives a high difference outlet between inlet and outlet temperature hot gas. Also its clear that the temperature difference recorded between 5 K at $Br=0.3$ and 44 K at $Br=1.3$ for all inclination angles except 90° .

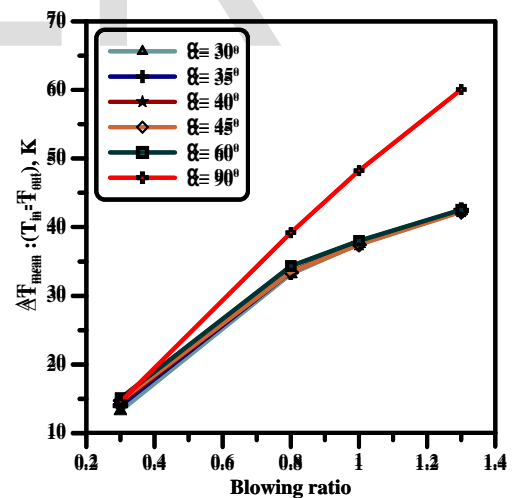


Fig. 4 variation of mean temperature difference with blowing ratio at different inclination angles.

4.1.3 Film cooling effectiveness

Figures (5-8) show the variation of cooling effectiveness along dimensionless distance (s/d) at blowing ratios (0.3,0.8,1,1.3) and different inclination angles (from 30° to 90°). It's clear that the effect of inclination angle on cooling effectiveness is small at low blowing ratios as depicted in Fig. (5). And by increasing the blowing ratio the effect of inclination angle increases gradually to

reach its best effect at $Br=1.3$. The cooling effectiveness increases as the inclination angle increases till angle of 60° , this is agreeing with mean film cooling effectiveness as shown in the figure (10). The highest value of cooling effectiveness is (0.945) occurring at inclination angles of (60°) for all blowing ratios. This is due to the effect of mainstream curvature momentum which forces the coolant toward the blade surface to construct film cooling, and by increasing the inclination angle more than 60° , the film cooling effectiveness decreases to reach its minimum at inclination angle of 90° . This is due to the effect of normal component of coolant momentum, at high inclination and high blowing ratio, interrupting the mainstream but main stream blowing back the coolant toward the blade surface and makes recirculation near the jet exit. In that case it can be considered that the film-cooling does not created. The mixture of coolant and hot gas is made by turbulence of working fluid, diffusivity phenomena and recirculation causes to decrease cooling effectiveness as shown in the figure (9) which agree with [15], [8], [11].

It can be concluded that both film cooling and mixture layers occur at all different blowing ratios, inclination angles at different distances on the blade surface depending upon the inclination angle and blowing ratio.

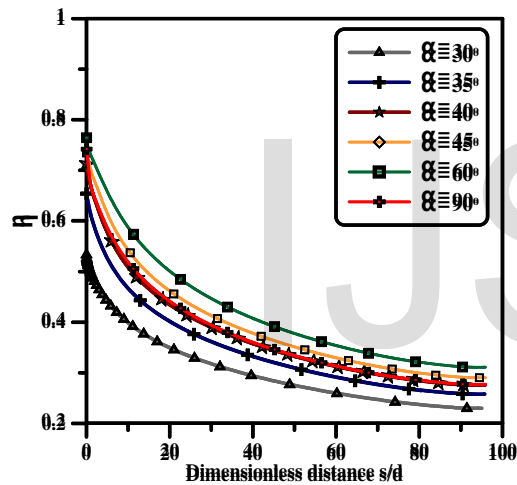


Fig. 5 Relation between (η) and s/d at $Br=0.3$

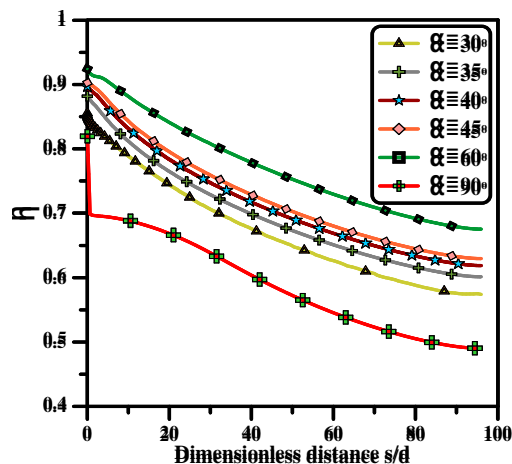


Fig. 6 Relation between (η) and s/d at $Br=0.8$

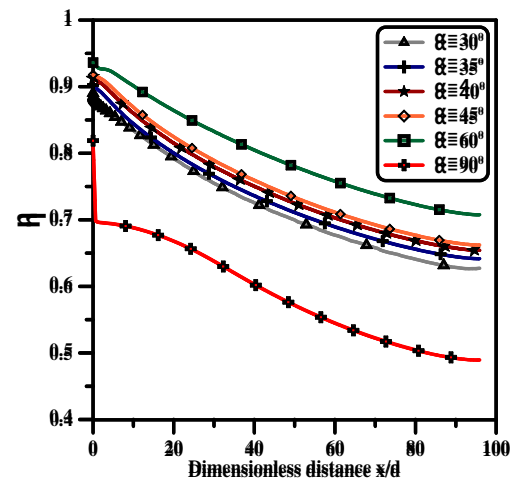


Fig. 7 Relation between (η) and s/d at $Br=1$

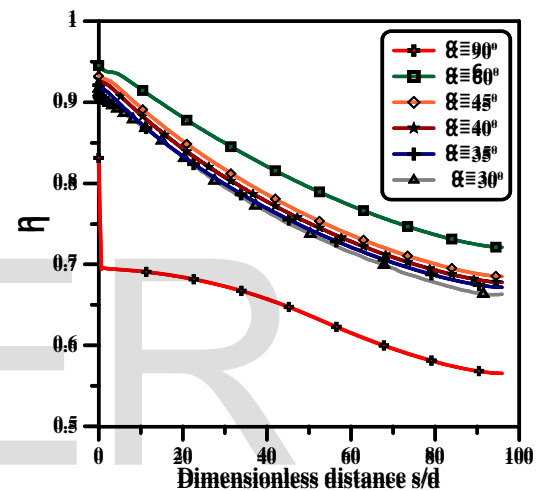


Fig. 8 Relation between (η) and s/d at $Br=1.3$

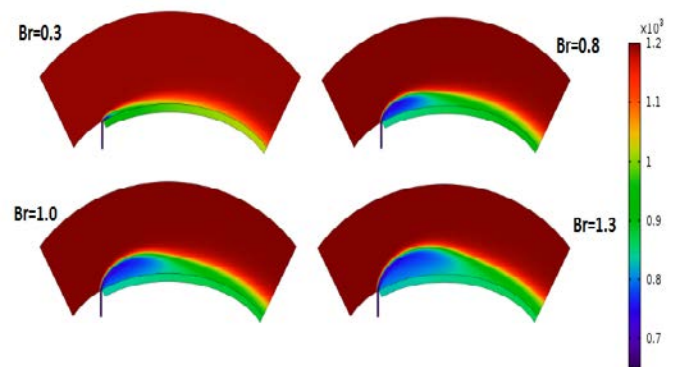


Fig. 9 Vortices at angle 90° and different blowing ratio

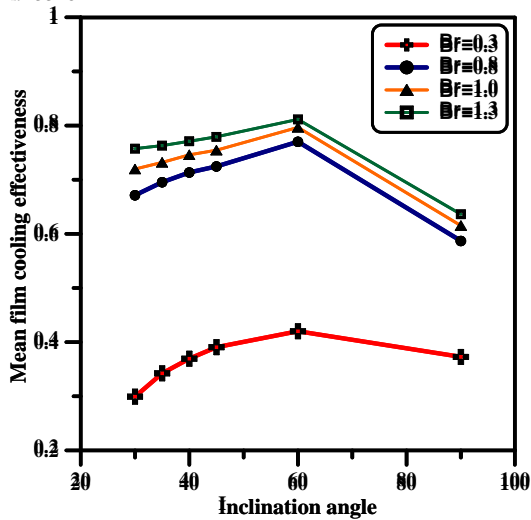


Fig. 10 Relation between mean film cooling effectiveness and Blowing ratio at different inclination angle

4.1.4 Heat transfer

Figures (11-14) depict the variation of local Nusselt number along the blade surface at different inclination angles with the Reynold number. As shown in these figures, by increasing the inclination angle the local Nusselt number decreases, for all blowing ratios, which means that the rate of heat transfers from hot gases to the blade surface decrease which agrees with the results obtained from the film cooling effectiveness analysis. Also it can be noticed a non-stability of the behavior of the local Nusselt number at inclination angle of 90° due to formation of vortices and recirculation. These vortices increase the heat transfer in some regions and decrease it in another which may cause a thermal stress due to non-uniform temperature distribution which agrees with [9]. Also the results showed that the best stable Nusselt number (lowest) is at inclination angle of 60° and $Br=1.3$.

Figure (15) concludes the average Nusselt number for different inclination angles with the Blowing ratio. As shown in this figure, the lowest average Nusselt number is at inclination 60° , and the higher Nusselt number is at 30° .

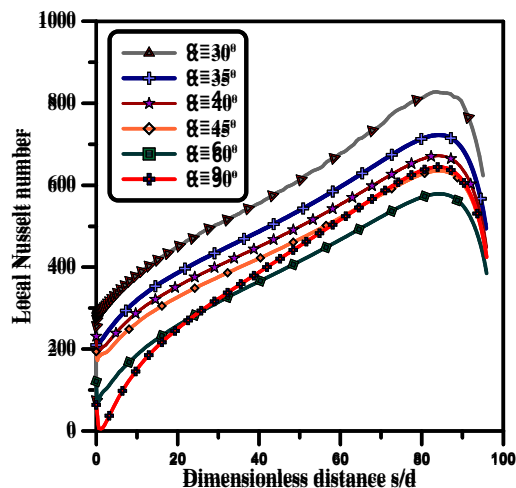


Fig. 11 Relation between Nu and α at $Br=0.3$

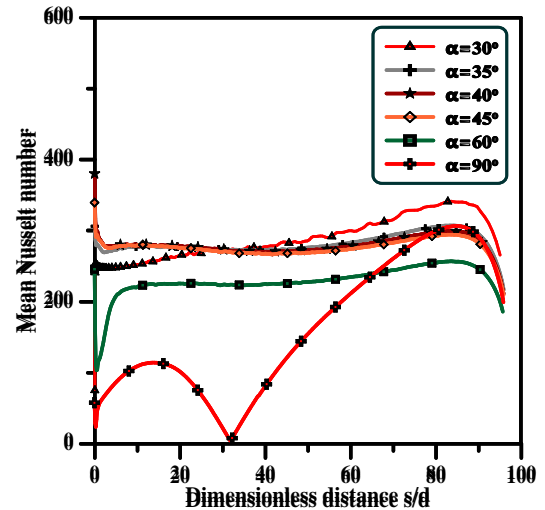


Fig. 12 Relation between Nu and α at $Br=0.8$

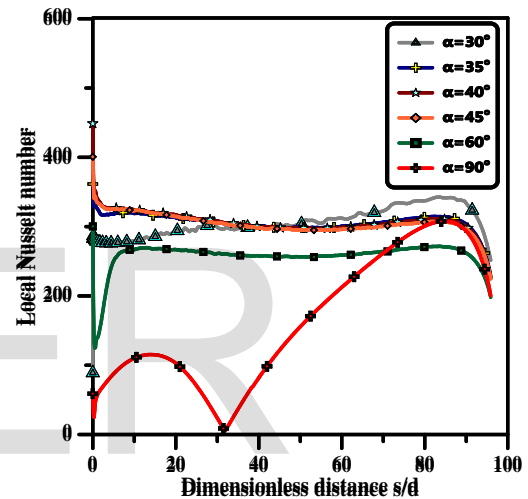


Fig. 13 Relation between Nu and α at $Br=1$

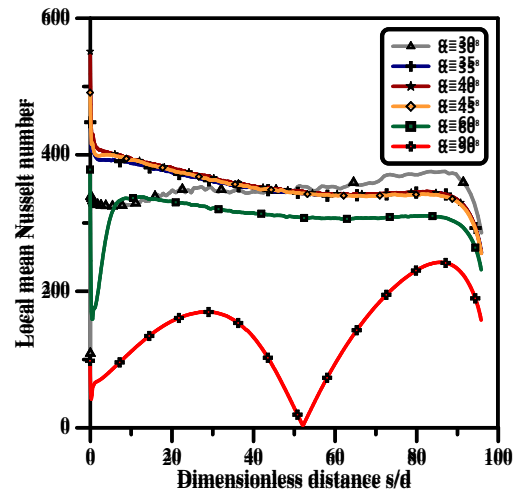


Fig.14 Relation between Nu and α at $Br=1.3$

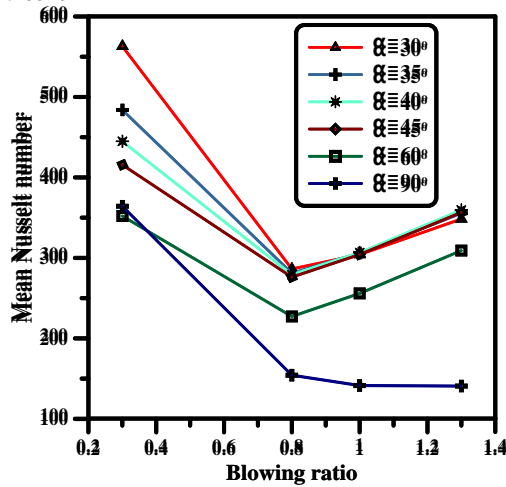


Fig. 15 Relation between Nusselt number and different blowing ratio at different inclination angle

4.2 Pressure Losses

In the gas turbine, the key parameters of the gas turbine performance are pressure and temperature, so, pressure drop is considered an effective parameter which should be investigated to demonstrate the effect of the film cooling on the flow outlet pressure. Figure (16) shows the pressure drop with blowing ratio variation at different inclination angles. It is clear that for the inclination angles from 30° to 60° , the pressure drop varied with small values that affected by the inclination angle variation for all blowing ratios. Also, by increasing the blowing ratio, the pressure drop decreases for inclination angles 30° - 60° . This due to the increasing of coolant flow rate which increases the exit pressure. The final pressure outlet is a combination between the decrease in pressure due to friction and disturbance caused by the coolant and the increase in pressure due to increase the coolant flow rate. On the other hands, for the inclination angle of 90° , the pressure drop is very high it may be due to the penetration of the coolant into the main stream which makes a noticeable disturbance for all blowing ratios. These disturbances can be considered as obstacle ribs.

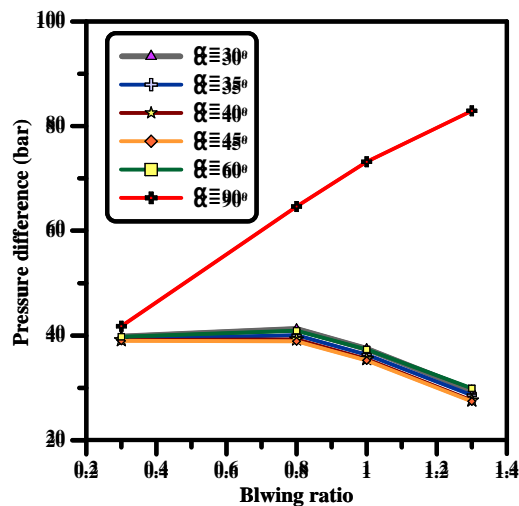


Fig. 16 Pressure drop through the flow channel with the Br at different inclination angles

5-Conclusion

Numerical simulation was conducted to investigate the film cooling effectiveness of a stationary elliptical blade. This investigation performed using a commercial software package, Comsol Multi-physics 5.2, by simulating the flow as a 2D domain for inclination angles ranged from 30° to 90° and blowing ratios from 0.3 to 1.3. the output of this investigation can be concluded as following:

1. Film cooling is an effective tool when used for cooling the stationary turbine blade which gives a cooling of the blade surface by %37.2 from that without film cooling.
2. The best mean film cooling effectiveness occurs at inclination of 60° and blowing ratio of 1.3 with a value of 0.945.
3. The pressure drop is recorded for all inclination angles at different blowing ratios and the inclination angle 90° gives the maximum pressure drop for all blowing ratios.
4. For high blowing ratio, $Br > 0.8$, the pressure drop decreases due to the increasing in pressure by the coolant mass flow rate.
5. The inclination angle 90° is considered the worst inclination angle because of its low film cooling effectiveness, the thermal instability behavior, and high pressure drop.

NOMENCLATURE

Br: blowing ratio

d: hole diameter, mm

L: hole length, mm

P: pressure

S: arc length, mm

S_T : source term. $\text{Kg. } ^\circ\text{C/m}^3$

T: temperature, (k)

u : velocity components in Cartesian

$\overline{u'_i u'_j}$: turbulence Reynolads stress

V: velocity, (m/s)

(x, y): Cartesian coordinate

Y: normal component to mainstream gas direction

Greek latter's

α : inclination angle

β^* : model constants

Γ : diffusion factor

η : film cooling effectiveness

κ : von Karman constant

μ : dynamic viscosity of fluid

μ_m : molecular viscosity

μ_t : turbulent eddy viscosity

ν_t : kinematic turbulent viscosity

ρ : density (kg/m^3)

σ_k, σ_ω : model constants

Ω : specific dissipation rate of k

Subscripts

c: coolant

e: effective

g: mainstream hot gases

i, j: coordinate direction

in, out: inlet and out let of hot gas

k: turbulent kinetic energy

m: molecular

t: turbulent

ω : specific dissipation rate

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