Effectiveness of film cooling process on flat plate using multi-rows of cooling

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Abstract:

Film cooling process is one of the most important external cooling methods used for gas turbine blades. In the present study the effectiveness of multi – row film cooling process on flat plate was estimated. Three rows of film cooling were considered with three configurations which are: simple injection angle with uniform cooling holes distribution, compound injection angle with uniform cooling holes distribution and staggered distribution for film cooling holes with simple injection angle. The simulation of the three cases were performed for different Reynolds number under real operating conditions. Gambit – Fluent package was used for the numerical simulation. Three dimensional incompressible turbulent flow with k – Ɛ model for turbulence was used for the simulation. The results show that, the staggered distribution for the film cooling holes gives the best for effectiveness the cooled surface.

فعالية عملية التبريد الغشائي على صفيحة مستوية باستخدام صفوف تبريد متعددة

الملخص:

تعد عملية التبريد الغشائي واحدة من اهم عمليات التبريد الخارجي المستخدمة في ريش التوربين الغازي. تم في هذه الدراسة تحديد فعالية عملية تبريد غشائي لصفيحة مستوية. استخدمت ثلاثة صفوف تبريد مرتبة بثلاث طرق هي: زاوية حقن بسيطة مع توزيع منتظم لثقوب التبريد، زاوية حقن مركبة مع توزيع منتظم لثقوب التبريد وتوزيع متخالف لثقوب التبريد مع زاوية حقن بسيطة. تم التمثيل النظري لهذه الطرق الثلاث باستخدام قيم مختلفة لرقم رينولدز تحت ظروف تشغيل حقيقية. تم الحل العددي لهذه الحالات الثلاث باستخدام الحقيبة البرمجية فلونت .التمثيل العددي تم بفرض جريان ثلاثي البعد، لا انضغاطي ومضطرب مع استخدام الموديل الرياضي k-Ɛ لنموذج الاضطراب. بينت النتائج ان فعالية التبريد الافضل كانت لحالة التوزيع المتخالف لثقوب التبريد.

1-Introduction:

A great improvement in gas turbine efficiency in the recent was resulted from the increased of the temperature of the gases inlet to the turbine. This increase in the turbine inlet temperature results from the efficient cooling of gas turbine blades. So, the turbine inlet temperature increased to the range of (2000 K)[1]. External cooling of gas turbine blades by using film cooling process, represents one of the most efficient cooling techniques. Simulation of film cooling process was important for improving the effectiveness of the process, and as a result the gas turbine efficiency.

Different theoretical studies were performed for the simulation of the film cooling process on flat plate. Some of these studies are for single hole film cooling process [2,3,4,5], single row with multi holes [6,7,8] and multi rows with multi holes [9,10,11,12]. Most of these studies were performed under operating conditions far from the real operating conditions of gas turbine. Also, most of these studies were focused on single parameter which effects the effectiveness of the process, such as injection angle and holes distribution.

In the present study, the simulation is performed under real operating conditions and also, the effect of different parameters (simple injection angle ,compound injection angle and holes distribution) on the film cooling effectiveness are considered.

2- Mathematical formulation:

2-1 Geometry:

The geometry for the three cases are performed and all dimensions were explain as shown in the (Figure 1). starts from drawing of the geometry of three cases, where the dimensions of main stream channel are:(z=20mm, x=80mm, y=10mm) and the dimension of cooling chamber are: z=20mm, x=34mm, y=6mm). The nozzles (holes) is inclined with angle α, and the diameter of the hole is d, the distance between any hole and the vicinity one is d. For all cases, the diameter of the cylindrical cooling hole is d=2mm with an inclination angle of $\alpha=20^{\circ}$, and the ratio of the length of the cooling hole to the diameter is 5.8. The configurations of the holes are :

1-Simple injection angle.

2-Staggered simple injection angle.

3-Compound injection angle.

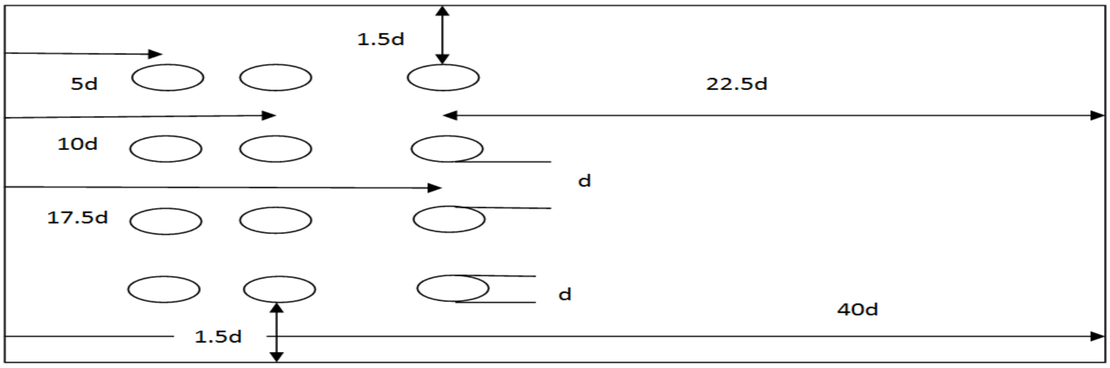

Figure 1 Simple injection angle configuration

2-2 Governing equations:

2-2-1 Conservation of Mass:

$$\frac{\partial}{\partial xi}(\rho \cup_{i}) = 0 \qquad (1)$$

2-2-2 Conservation of Momentum:

$$\frac{\partial}{\partial x_i}(\rho U_i U_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial xj} + \frac{\partial U_j}{\partial xi}\right) - \rho\overline{u_i u_j}\right] + F_i \qquad (2)$$

2-2-3 Conservation of Energy:

$$\frac{\partial}{\partial x_i}(c_p \rho u_j T) = \frac{\partial}{\partial x_j}\left[k\frac{\partial T}{\partial_{xj}} - \overline{\rho u_j t}\right] \qquad (3)$$

2-2-4 Cooling Effectiveness:(η)

$$\eta = T_{h,in} - T_f / T_{h,in} - T_{c,in} \qquad (4)$$

2-3 Grid dependency analysis:

For all previous cases three dimensional numerical simulation with turbulent flow are performed by using the CFD code "FLUENT" which based on finite volume approach to solve the partial differential equation(mass, momentum and energy). The first step of the simulation process is to establish the mesh size, so that the results obtained are grid independent. In the present study the numerical simulation model for the simple injection case are checked with different mesh sizes. The comparison between all the mesh sizes are based on the average surface temperature in the spanwise direction for different location in the stream wise direction which are (X=40 and 80mm) as shown in the Fig.4. From the figure, the minimum percentage error of the predicted temperature lies between the mesh volumeof (1150000) and the mesh volume (1300000). The percentage error between the two meshes for the three given locations is (0.09%) for (X=40mm) and error (0.2%) for (X=80mm). So the mesh size of (1150000) is used in the simulation in order to reduce the calculation time.

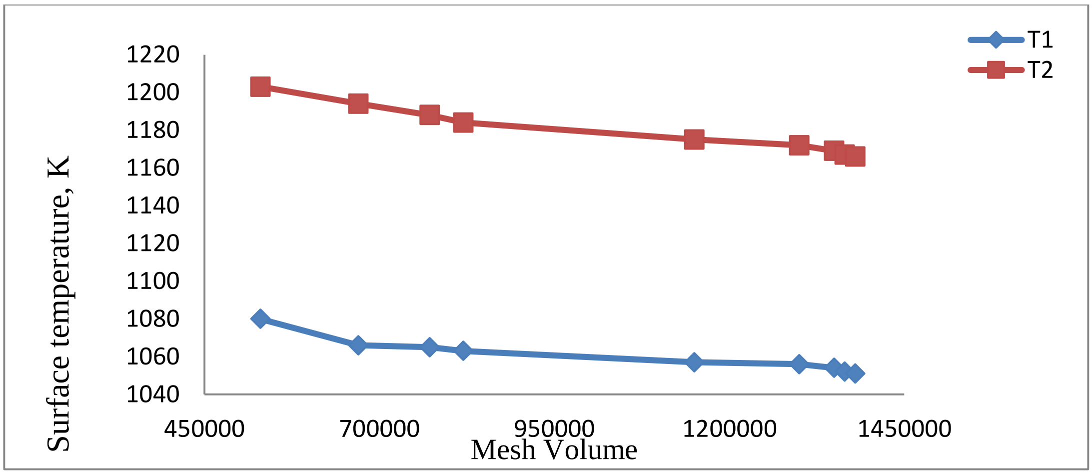

Fig.2. Grid independence for simple injection angle, B.R=0.5, Re=10000, α=20˚

Model validation:

Apreliminary investigation has been done to validate the present model with the results of Chenga etal.[2] The case study of Chenga was the simulation of film cooling process over a flat plate with single hole and simple injection angle. Different blowing ratio where used(0.5, 1, 1.5, 2) and compared between the film cooling effectevness in stream wise direction.which is on flat plate cooling with single cylindrical hole.The hole diameter is d=12.7mm with an inclination angle α=30˚, length to diameter ratio is 4, the main stream speed and temprature is 20 m/s and 300K respectively. Coolant temprature is 150K, with main stream turbulence intensity is 2%. The results of the film cooling effectiveness of the present simulation are compared with those obtained by Chenga. The comparison is shown in Figure.5. There is a good agreement with the Chenga results.[2]

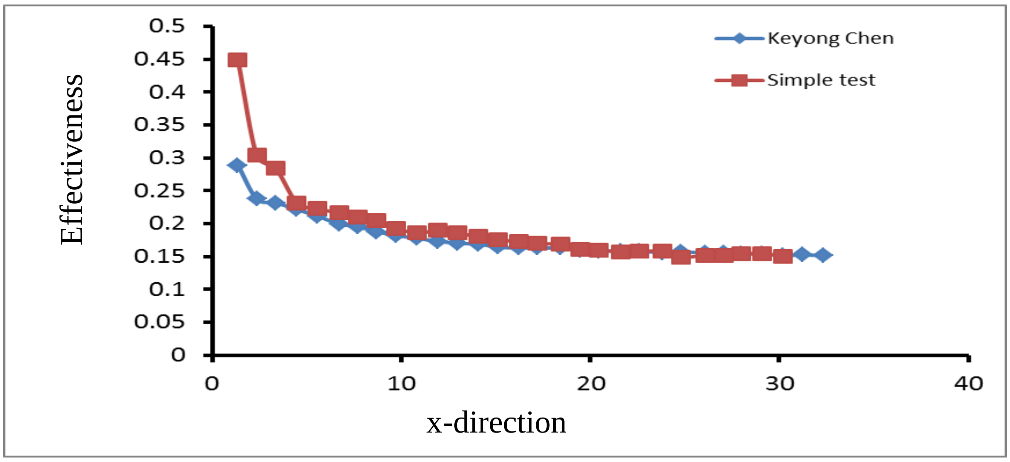

Fig.3. The validation of the present work with Chenge[2]

3- Boundary conditions:

3.1 Boundary condition for inlet main stream(hot gases):

1-The main stream temperature $T=T_{in,h}$=1500K.

2-Turbulence intensity is 5%.

3-The velocity $U=U_{in,h}$ =31, 62, 124, 248 and 310m/s. Each value corresponds to a certain value of Reynolds number. (for Re=10000, 20000, 40000, 80000 and 100000 respectively).

3.2 Boundary condition for inlet cooling stream:

1-The inlet cooling temperature $T=T_{in,c}$ =600K.

2-Turbulence intensity is 5%.

3-The velocity $U=U_{in,c}$= (7.299, 14.601, 29.1996, 58.464 and 73.08 m/s).

3.3 Outlet boundary conditions:

1- Outlet pressure is 5 bar.

3.4 Walls boundary conditions:

1- No-slip condition.

2- The walls are:

A- The bottom surface of main channel at constant temperature T= 1000K.

B- Other walls are insulated.

4- Results and discussion:

4-1 Stream wise effectiveness:

The countours of film cooling effectevness along the cooled flat plate surface at B.R=1.5, α=20˚, Reynolds number equal to 10000 & 100000. are given in Figures. (4 to 9), the red regions, represents the maximum effectevness when the surface covered by the cooling air only and this value decrease when the mixing with hot gases increase and this decreasing is represented by the yellow, green and white blue regions. The dark blue regions, represents the regions subjected to the hot gases only. Also, for all cases the lateral spread of the film cooling layer decreases with increasing of Reynolds number due to decreasing the penetration of the cooling air through the hot gases , while the axial spread is increased.

The average effectivness along a line in the stream wise direction located at (z=10mm) is given in table 1. From the table its clear that the staggered distrebution gives the best effectivness due to the good coverage of the cooling air along the cooled surface.

Table 1. Average streamwise effectiveness at(Z=10mm) at different Reynolds number.

Re	Eff.(Simple)	Eff.(Staggered)	Eff.(Compound)
10000	0.341	0.621	0.550
20000	0.3233	0.625	0.550
40000	0.313	0.628	0.5499
80000	0.305	0.629	0.5497
100000	0.303	0.630	0.5490

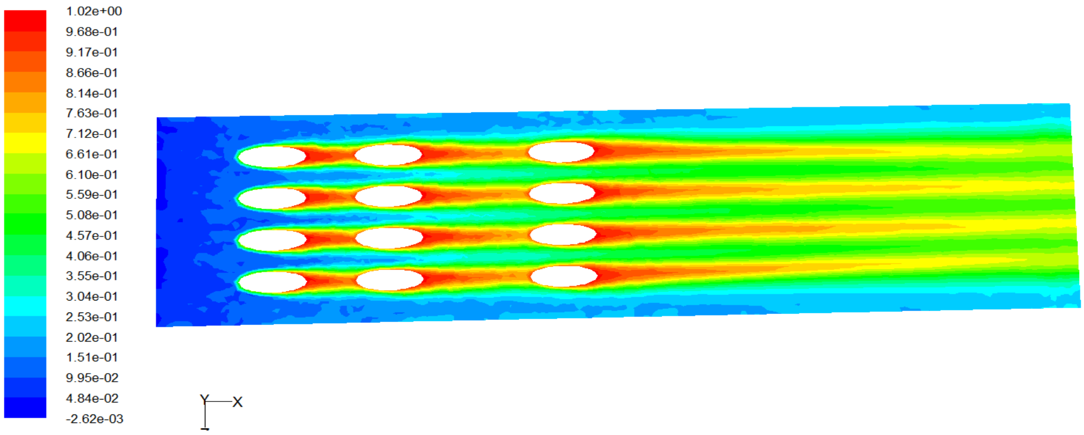

Fig.4 Contours of effectiveness at flat plate surface with simple injection angle, B.R=1.5, α=20˚ and Re=10000)(

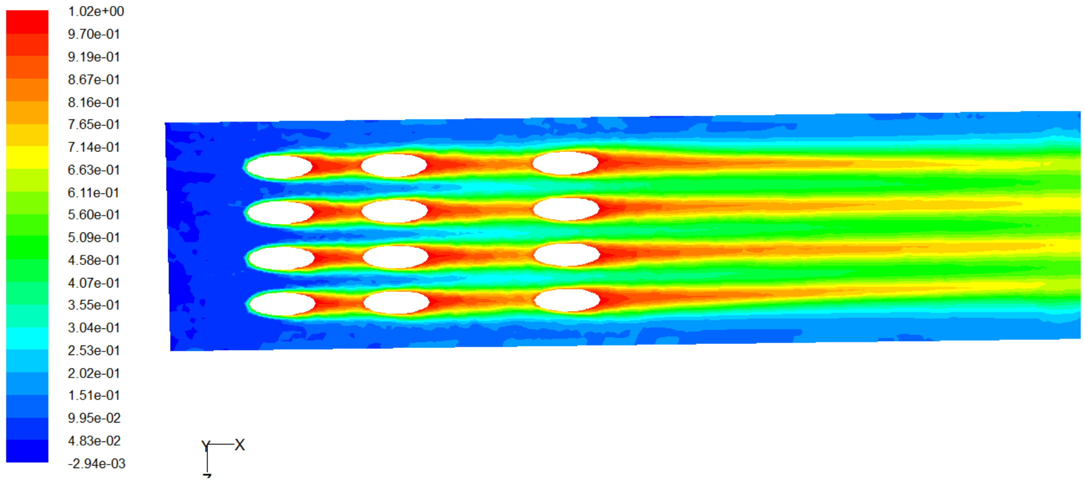

Fig.5 Contours of effectiveness at flat plate surface with simple injection angle, (B.R=1.5, α=20˚ and Re=100000)

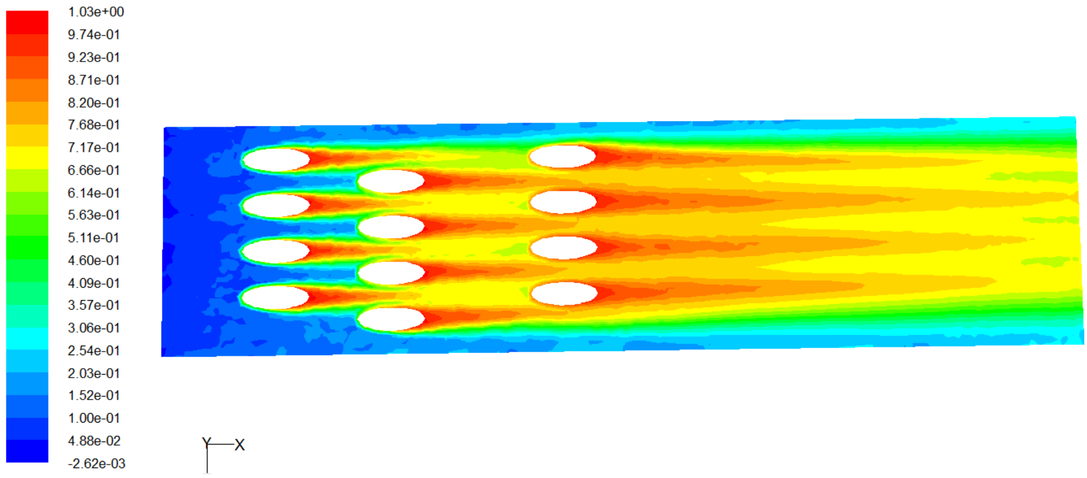

Fig. 6 Contours of effectiveness at flat plate surface with staggered simple injection angle, (B.R=1.5, α=20˚ and Re=10000)

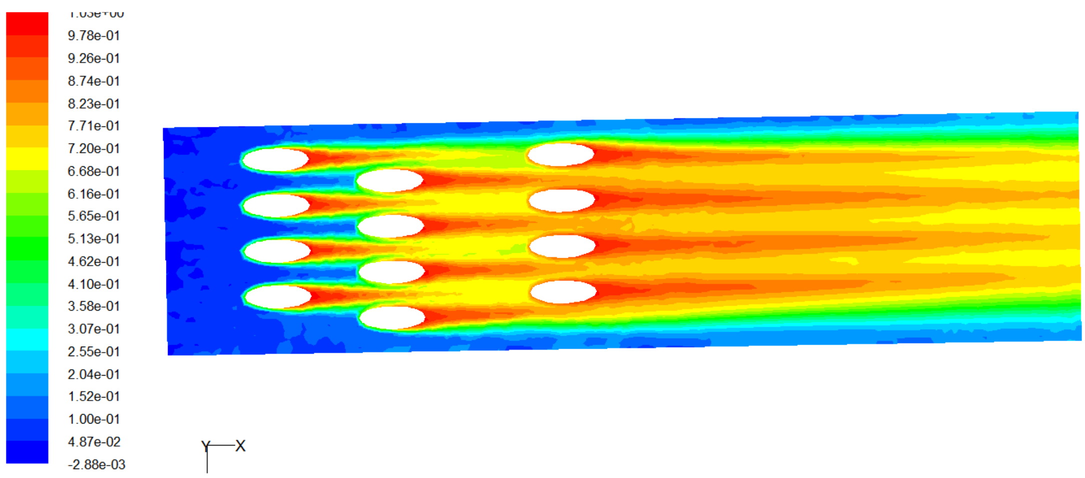

Fig. 7 Contours of effectiveness at flat plate surface with staggered simple injection angle, (B.R=1.5, α=20˚ and Re=100000)

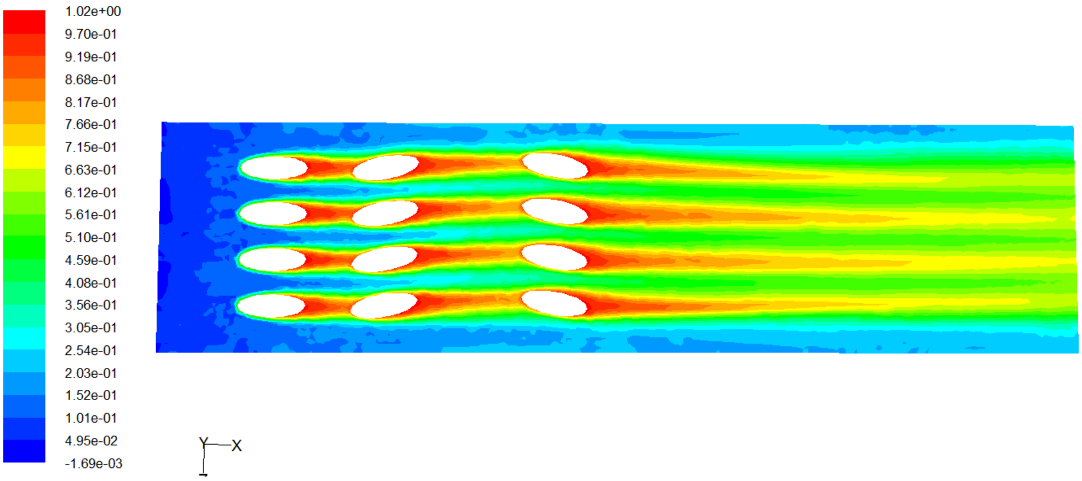

Fig. 8 Contours of effectiveness at flat plate surface with compound injection angle, (B.R=1.5, α=20˚, β=10˚ and Re=10000)

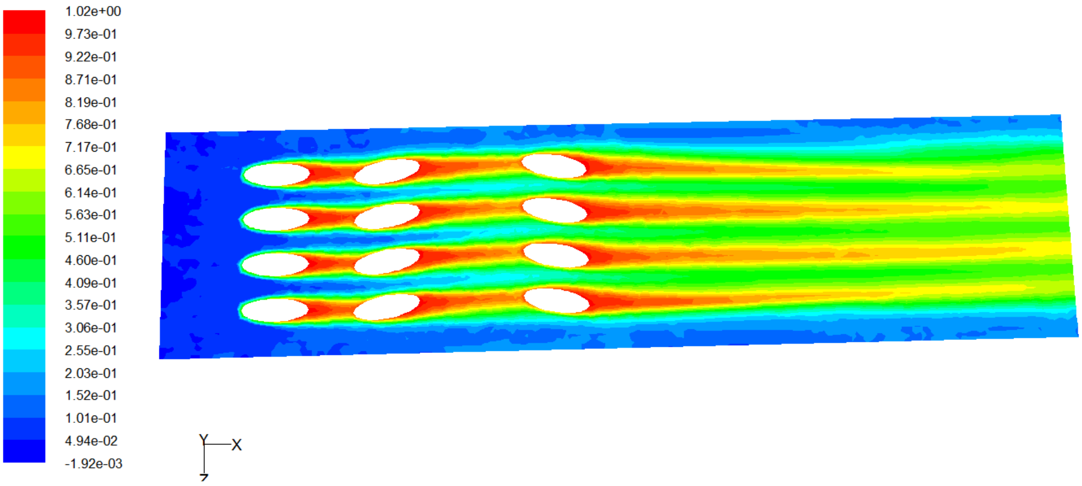

Fig. 9 Contours of effectiveness at flat plate surface with compound injection angle, (B.R=1.5, α=20˚, β=10˚ and Re=100000)

4-2 Span wise effectiveness:

The variation of film cooling effectiveness in the spane wise direction at different locations with stream wise direction at B.R=1.5, α=20˚, Reynolds number 10000 & 100000 are given in the Figs. (10 to 15), where simple case Figs (10 & 11), staggered case Figs. (12 & 13) and compound case Figs. (14 & 15). The variation of the film cooling effectiveness is given at the locations (X=15, 25, 40, 60 and 80mm). Also, the maximum values of effectiveness at the film cooling holes, and beyond the holes there is decrease in the values of film cooling effectiveness due to the mixing of the two streams.The staggered case predicts the optimum values of the film cooling effectiveness along the cooled and protection flat plate surface due to the distribution of the cooling holes. There is accummulated effect between the successive rows results in good spread of the film cooling layer.

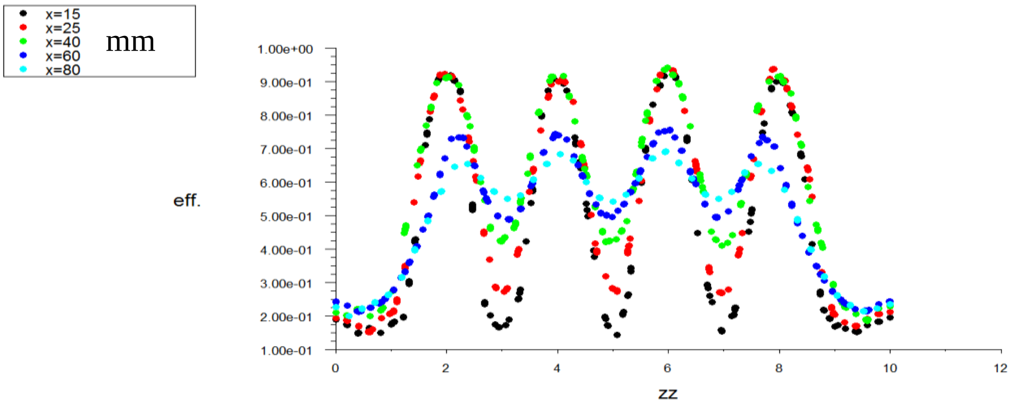

Fig. 10 Effectiveness for simple injection angle, (B.R=1.5, α=20° and Re=10000)

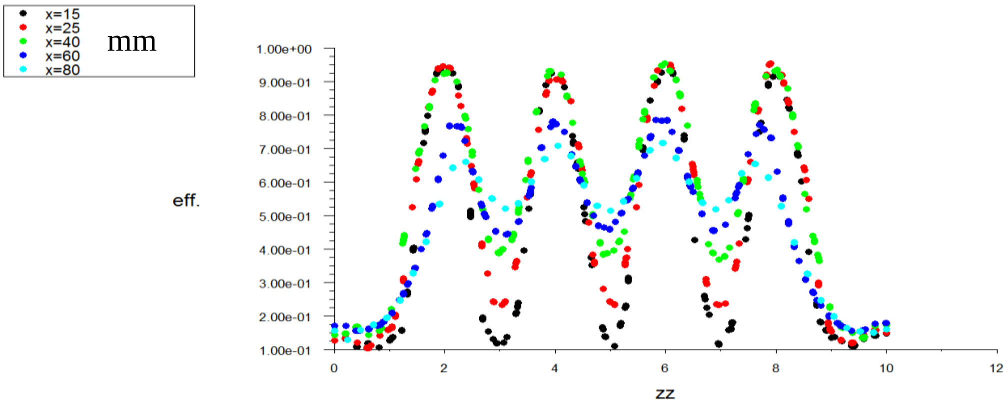

Fig. 11. Effectiveness for simple injection angle, (B.R=1.5, α=20° and Re=100000)

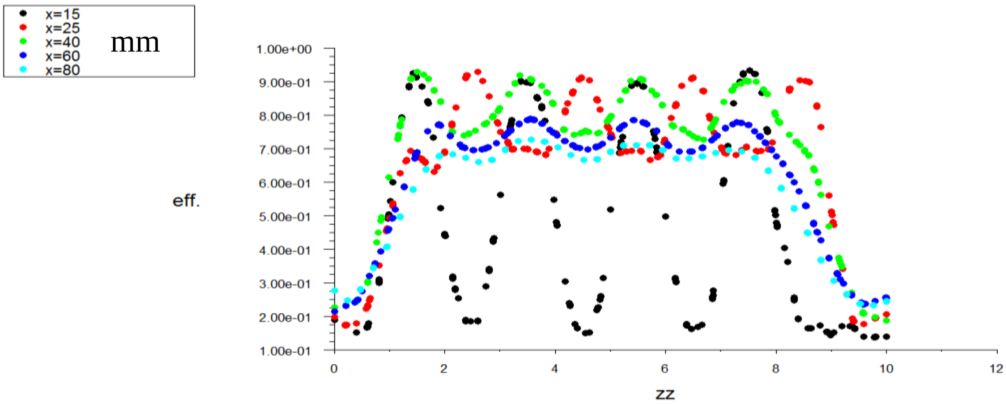

Fig. 12. Effectiveness for staggered simple injection angle, (B.R=1.5, α=20° and Re=10000)

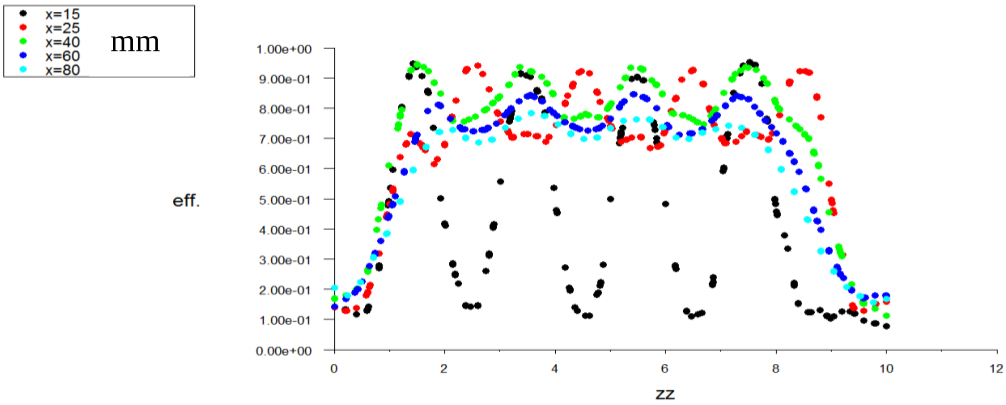

Fig. 13. Effectiveness for staggered simple injection angle, (B.R=1.5, α=20˚ and Re=100000)

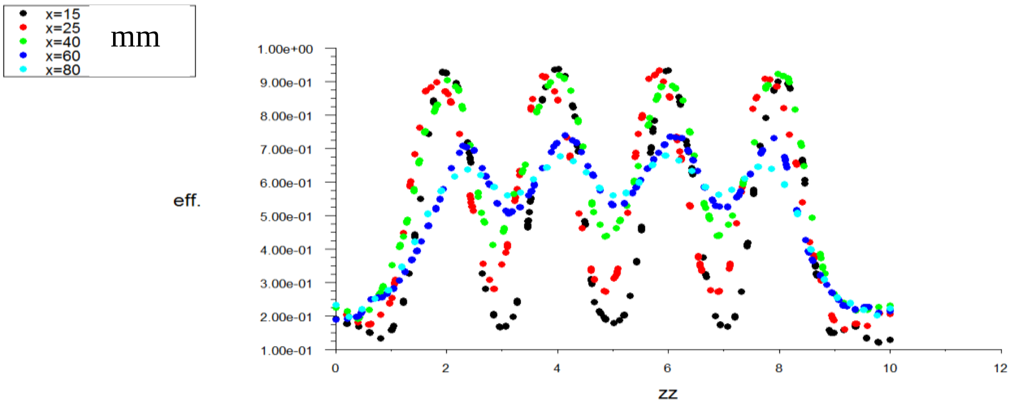

Fig. 14. Effectiveness for compound injection angle, (B.R=1.5, α=20˚, β=10˚ Re=10000)

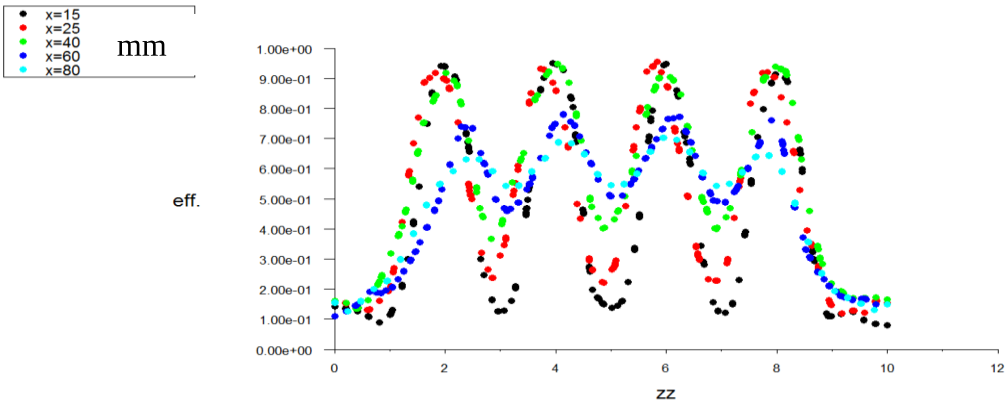

Fig. 15. Effectiveness for compound injection angle, (B.R=1.5, α=20˚, β=10˚ and Re=100000)

5- Conclusions:

The film cooling flow over flat plate at constant temperature is investigated using numerical method (Finite Volume Method) with software package (Fluent). It is found that the main parameter that effect on the performance are Reynolds number, blowing ratio and holes configuration where three holes configurations (Simple distribution, Staggered distribution and Compound distribution) are studied. It can be concluded that from the present study:-

1- The staggered injection gives maximum effectiveness.

2- Increment of Reynolds number leads to decrease the effectiveness, except the staggered case.

Nomenclature:

ρ**:** Fluid density (kg/m$^{3)}$

C_p: Specific heat at constant pressure(J/kg. k)

P: Pressure (Pa)

F_i:External forces per unit area in the x, y , z direction (N/m^2)

d: Hole diameter (m)

k: Thermal conductivity (W/m .K)

μ_t: Turbulent viscosity (N.s/m^2)

U: Steady mean velocities in the x direction (m/s)

T: temperature(K)

T_{inh}: Hot stream inlet temperature (K)

T_{inc}: Cold stream inlet temperature (K)

T_f: Adiabatic Wall Temperature(K)

Tu: Turbulent intensity

A: Inclination angle(degree)

β: Orientation angle(degree)

k-ε: turbulent model

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