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Analysis on Gas Turbine Blade Cooling by Compressed Air Channels using CFD Simulation

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ABSTRACT

Enhancement of gas turbine performance can be achieved by increasing the working fluid temperature. On other hand, the level and variation in the temperature within the blade material which causes thermal stresses, must be limited to achieve reasonable durability goals. Therefore, there is a critical need to cool the blades for safe operation by internal air flow passages. In this study, CFD technique was employed to investigate the temperature distribution in at different operational conditions. The blade was digitized to get the exact dimensions in the form of AutoCad drawing which was then exported to GAMBIT for discretization and to FLUENT for simulation. Flowing into a rectangular 9×18 mm channel, 400 K compressed air is used to cool the blade while the blade is spinning in hot gas of 1700 K. The temperature distribution was compared with the results previously obtained by using analytical-finite difference coupled method. The results show that the temperature difference is less than 5% at the root of the blade and 15.9% at the channel of height 157.7 mm. Further simulation and analysis of a ribbed channel with rib angle, $\alpha = 60°$ and rib blockage ratio, $e/D_h = 0.078$ have been carried out and compared with previous analytical results. Ribbed channel was compared with smooth channel coohng. The results showed that there is a decrease in the blade material temperature which improves the efficiency by 8.68% when using two-opposite rib walls on the 18 mm wide side of the channel.

Key words: Blade cooling, numerical analysis, gas turbines, enhanced heat transfer, CFD, thermal analysis

INTRODUCTION

Gas Turbine engines are designed to continuously and efficiently convert the energy of fuel into useful power and are developed into very reliable, high performance engines. Now, gas turbines are widely used in power plants, marine industries as well as for aircraft propulsion.

Starting from early 1970s, many researches were carried out by aircraft and power generation gas turbine designers aiming at increase the combustion chamber exit and hence the high-pressure turbine stage inlet temperatures. By increasing the combustion chamber exit temperature, the engine thermal efficiency can be improved and fuel consumption can be reduced.

The cooling technology can be divided into two techniques that are internal and external cooling. For external cooling, a cooled fluid is injected as a jet to interact with the hot external fluid flow (Bounegta *et al*., 2010). For the internal cooling, in order to increase the heat transfer from turbine blade to the coolant air, different technologies were used like ribs, Pin-fin and dimples cooling and impingement cooling (Gao and Sunden, 2001; Dahlquist, 2008; Donald, 2008).

The temperature distribution of compressed air can be categorised into two different cooling channel configurations. The first type is called smooth due to the non-ribbed channel walls. Meanwhile, for the second type, the channel walls are artificially roughened by regular repeated ribs as shown in Fig. 1.

Factors like channel aspect ratio, rib configuration and flow Reynolds number will affect the heat-transfer performance in a stationary ribbed channel. In general, typical ribs heights that are used for experimental studies, Fig. 2, are around 5-10% of channel hydraulic diameter. p/e ratio varying from 7 to 15 (Han, 2004).

Al-Kayiem and Ghanizadeh (2011) have published detailed analysis on the GT blade cooling with smooth and different ribbed channel cases. The set of equations was discretized and solved numerically by finite difference method solved by matrix inversion. They have concluded that channels ribbed with 60° angle and rib blockage ratio, $e/D_h = 0.078$ produced the best performance based on highest convection heat transfer coefficient.

The objective of this paper is to simulate the gas turbine blade cooling by using finite volume method employing the commercial ANSYS-FLUENT software. The investigation was proposed to cover the thermal analysis of the entire blade body at smooth and ribbed channels. The same operational conditions employed by Al-Kayiem and Ghanizadeh (2011) has been adopted her.

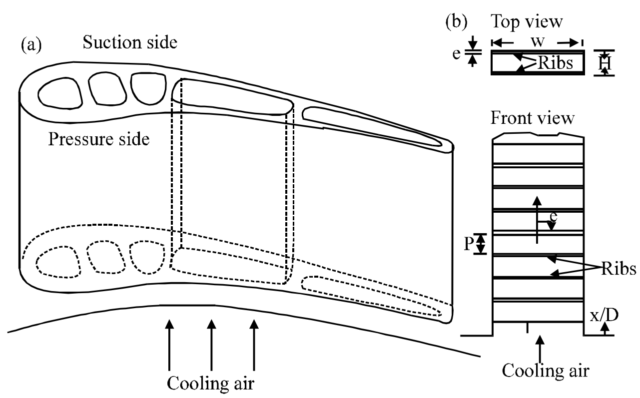

Fig. 1(a-b): (a) Typical coolant channel in turbine airfoils and (b) Internal arrangement (Han *et al*., 2000)

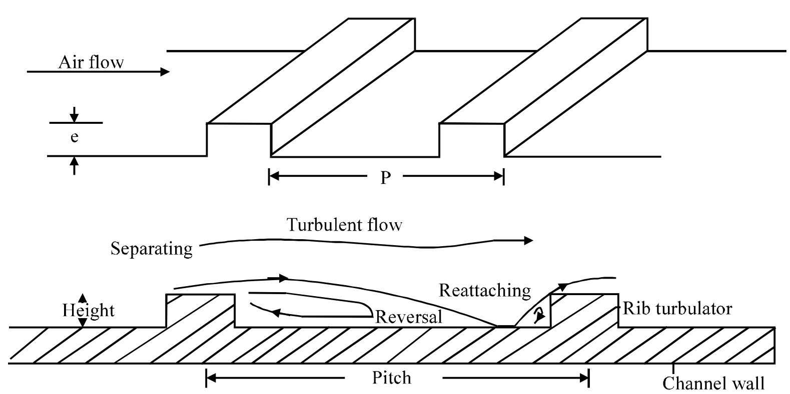

Fig. 2: Scheme of flow separation and rib orientations in heat-transfer coefficient enhancement (Han, 2004)

MATERIALS AND METHODS

The methodology of the present study is entirely numerical. Some measurements have been involved to identify the profile of the blade.

The blade model: The selected blade for the current analysis is 143 MW ABB GT13E2 supplied by Lumut Power plant-Malaysia. A Laser digitizer is used to obtain the exact profile of the blade in three dimensions, where the airfoil surface points are captured at different 210 mm span wise locations. The matrix of profile points is exported to AutoCad to model the blade and the model then exported to GAMBIT for discretization.

The cooling channel: The cooling channel has rectangular cross section. The size of the channel is selected as 18×9 mm and its height is 210 mm. The Hydraulic Diameter of the cooling channel, D_h is 0.012 m.

The ribs: The specifications of the ribbed channel used are chosen based on the highest predicted convection coefficient h_{ribbed} = 559.32 W m^{-2} K case which is at rib blockage ratio, e/D_h = 0.078, pitch-to-rib-height ratio p/e = 8 and rib angle α = 60° (6, 7). Accordingly, the ribs dimensions are height, e = 0.936 mm and pitch, p = 7.488 mm. Hence, the number of ribs in each side of the cooling channel becomes 26. With that, the configuration of the ribbed side in the cooling channel is as shown in Fig. 3.

Numerical implementation: The digitized shape of the blade is converted to 3-D drawing by AUOCAD and then to 3-D model in GAMBIT. Then, the channel is introduced in the model as shown in Fig. 4. Ribbed channels were also modeled and considered since the work requires comparison between smooth and ribbed channels.

The grid independency was determined. This is because with a correct size of grid meshing, the total elements can be reduced. With fewer totals of elements, the simulation can be run smoothly without large load exerted on the computer. This can also reduce the time used for simulation.

There are three variables in the size function to be looked into; which are starting size, growth rate and size limit. The selection of the size function on the blade will be stopped when the temperature differences exceed 5%. Once the size function on the blade is determined, the size function on the channel will be considered.

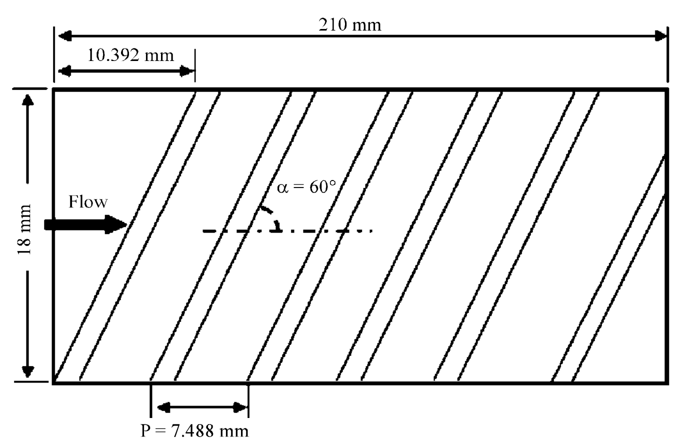

Fig. 3: Configuration of rib on the channel wall

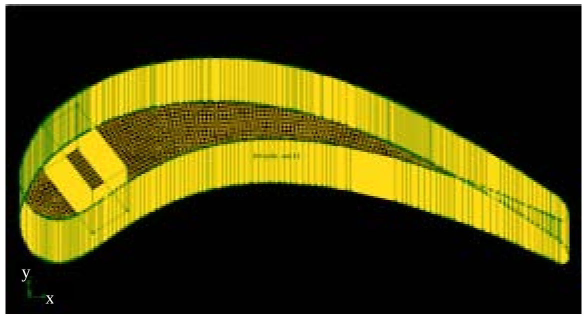

Fig. 4: 3-D model of the blade with the channel

The boundary conditions adopted for the simulation are based on a typical gas turbine operational environment as following:

- Temperature of hot gases attacking the blade is 1700 K
- Temperature of compressed air (T_a) entering the blade root is 400 K
- Convection heat transfer coefficient (h_g) for the hot gases is 1000 W m^{-2} K^{-1}
- Mass flow rate of compressed air entering the channel is 0.01 kg sec^{-1}
- Thermal conductivity of the blade metal is assumed to be 25 W m^{-1} K

RESULTS AND DISCUSSION

Thermal analysis the key to study the behaviour of the materials subjected to high temperature medium, like the case of the GT blades. This analysis will allow the designer to create appropriate cooling techniques to enhance the performance of the GT. A validated CFD analysis is representing a promising tool for thermal analysis, as the case of the present study. One of the requirements in the CFD simulation technique is the grid independency on the results.

Grid independency test: For the grid independency, two criteria are used to choose the size function for blade as follows:

- The temperature (if it does not have error in meshing)
- The total number of elements

Three points (A, B and C) on the blade, as in Fig. 5, are selected to check on the variation and accuracy of the temperatures by varying the grid structure and element numbers. Start size, growth rate and size limit are the variables to be changed until a maximum temperature difference of not more than 5% is obtained. If the blade cannot be meshed for a bigger growth rate, then the previous size of growth rate will be chosen.

Blade size function: Table 1 shows the temperature differences for different blade size functions. From Table 2 and 3, for a constant growth rate of 1, the temperature does not affect much on the meshed blade although the size limit is changing. Thus, the growth rate was increased to 3, 6, 9 and 12 for different size limit of 0.9, 3, 6, 9 and 90.

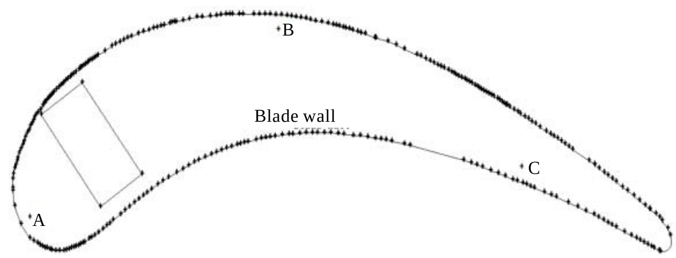

Fig. 5: Points A, B and C for grid independency checking

Table 1: Size function variable for blade with different growth rate

Size function			Total elements		Temperature (K)		
Start size	Growth rate	Size limit	Blade	Channel	Point A	Point B	Point C
0.9	1	0.9	560196	46800	1410.4	1410.4	1410.4
0.9	1	3	560196	46800	1410.4	1410.4	1410.4
0.9	1	6	560196	46800	1410.4	1410.4	1410.4
0.9	1	9	560196	46800	1410.4	1410.4	1410.4
0.9	1	90	560196	46800	1410.4	1410.4	1410.4
0.9	3	0.9	560196	46800	1410.2	1410.2	1410.2
0.9	3	3	164736	46800	1410.4	1410.4	1410.4
0.9	3	4.5	Error in meshing				
1.8	3	3	162162	46800	1386.5	1386.5	1386.5
0.9	6	0.9	560196	46800	1414.2	1414.2	1414.2
0.9	6	3	Error in fluent-diverge				
0.9	6	6	Error in meshing				
0.9	6	9	Error in meshing				
0.9	9	0.9	560196	46800	1414.2	1414.2	1414.2
0.9	9	3	165438	46800	Error in fluent		
0.9	9	6	Error in meshing				
0.9	9	9	Error in meshing				
0.9	12	0.9	560196	46800	1414.2	1414.2	1414.2
0.9	12	3	167544	46800	1414.2	1414.2	1414.2
0.9	12	6	Error in meshing				
0.9	12	9	Error in meshing				

The final selected size function with starting size of 0.9 is 0.9-3-3. This is because it has less total elements, so it reduces the load of the software during fluent simulation. Starting size of 0.9 and 1.8 are used for comparison after starting size function 0.9 has been chosen (0.9-3-3). Starting size function of 1.8 is to be considered because (1.8-3-3) has a lower number of total elements which is 162162, compared to size function (0.9-3-3) which has 164736 elements. Size function of 0.9-3-3 and 1.8-3-3 will be used to determine the channel size function.

Channel size function: The blade size function (0.9-3-3) and (1.8-3-3) are now be used to investigate the best size function for the channel. Table 4 shows the channel size function configuration meshing. The error that occurs during meshing is due to the size limit of the channel which does not comply with the starting size and growth rate.

Table 2: Size function variable for blade with same size limit for comparison

Size function			Total elements		Temperature (K)		
Start size	Growth rate	Size limit	Blade	Channel	Point A	Point B	Point C
0.9	1	0.9	560196	46800	1410.4	1410.4	1410.4
0.9	3	0.9	560196	46800	1414.2	1414.2	1414.2
0.9	6	0.9	560196	46800	1414.2	1414.2	1414.2
0.9	9	0.9	560196	46800	1414.2	1414.2	1414.2
0.9	12	0.9	560196	46800	1414.2	1414.2	1414.2
0.9	1	3	560196	46800	1410.4	1410.4	1410.4
0.9	3	3	164736	46800	1410.4	1410.4	1410.4
0.9	6	3	Error in fluent-diverge				
1.8	9	3	165438	46800	Error in fluent		
0.9	3	3	162162	46800	1386.5	1386.5	1386.5
0.9	12	3	167544	46800	1414.2	1414.2	1414.2
0.9	3	4.5	Error in meshing				
0.9	1	6	560196	46800	1410.4	1410.4	1410.4
0.9	6	6	Error in meshing				
0.9	9	6	Error in meshing				
0.9	12	6	Error in meshing				
0.9	1	9	560196	46800	1410.4	1410.4	1410.4
0.9	6	9	Error in meshing				
0.9	9	9	Error in meshing				
0.9	12	9	Error in meshing				

Table 3: Channel size function configuration meshing

Start size	Growth rate	Size limit	Blade size function	Meshing (in gambit)
0.9	1	0.9	0.9-3-3	✓
0.9	1	1.8	1.8-3-3	✓
0.9	1	0.9	0.9-3-3	✓
0.9	1	1.8	1.8-3-3	✓
0.9	2	0.9	0.9-3-3	✓
0.9	2	1.8	1.8-3-3	✓
0.9	2	0.9	0.9-3-3	✓
0.9	2	1.8	1.8-3-3	Error
0.9	3	0.9	0.9-3-3	✓
0.9	3	1.8	1.8-3-3	✓
0.9	3	0.9	0.9-3-3	✓
0.9	3	1.8	1.8-3-3	✓
1.8	1	0.9	0.9-3-3	Error
1.8	1	1.8	1.8-3-3	Error
1.8	1	0.9	0.9-3-3	✓
1.8	1	1.8	1.8-3-3	Error
1.8	2	0.9	0.9-3-3	Error
1.8	2	1.8	1.8-3-3	Error
1.8	2	0.9	0.9-3-3	✓
1.8	2	1.8	1.8-3-3	Error
1.8	3	0.9	0.9-3-3	Error
1.8	3	1.8	1.8-3-3	Error
1.8	3	0.9	0.9-3-3	✓
1.8	3	1.8	1.8-3-3	Error

Table 4: Size function variable for channel

Size function				Total element		Temperature (K)		
Start size	Growth rate	Size limit	Blade size function	Channel	Blade	Point A	Point B	Point C
0.9	1	0.9	0.9-3-3	46800	164736	1237.8	1383.2	1383.3
0.9	1	0.9	1.8-3-3	46800	162162	1468.9	1386.7	1386.7
0.9	1	1.8	0.9-3-3	46800	164736	1382.7	1382.7	1382.7
0.9	1	1.8	1.8-3-3	46800	162162	1468.3	1382.7	1386.2
0.9	2	0.9	0.9-3-3	46800	166374	1390.3	1390.3	1390.3
0.9	2	0.9	1.8-3-3	46800	162162	1468.7	1386.5	1386.5
0.9	2	1.8	0.9-3-3	33507	155052	1414.0	1414.0	1414.0
0.9	3	0.9	0.9-3-3	46800	164736	1383.3	1383.3	1383.3
0.9	3	0.9	1.8-3-3	46800	162162	1458.7	3386.5	1386.5
0.9	3	1.8	0.9-3-3	33507	155052	1398.2	1398.2	1398.2
0.9	3	1.8	1.8-3-3	10530	78507	1359.8	1359.8	1359.8
1.8	1	1.8	0.9-3-3	29784	147606	1362.4	1362.4	1362.4
1.8	2	1.8	0.9-3-3	29784	147606	1362.4	1362.4	1362.4
1.8	3	1.8	0.9-3-3	29784	147606	1362.4	1362.4	1362.4

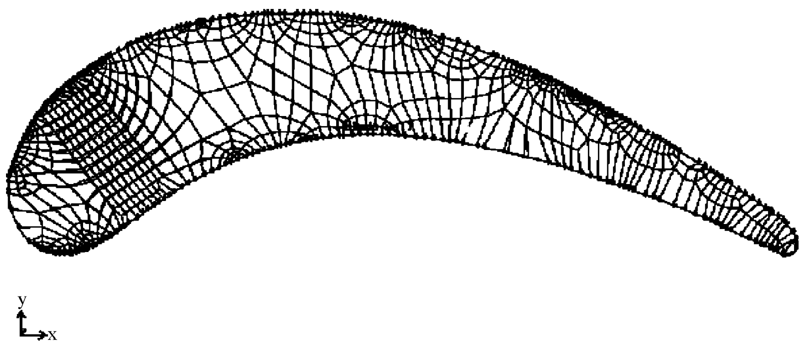

Fig. 6: The optimum meshing criteria with channel size function 0.9-3-1.8 and blade size function 1.8-3-3

Table 4 shows the temperature differences for different channel size functions. Channel size function 0.9-3-1.8 and blade size function 1.8-3-3 has been chosen for the simulation. Points A, B and C at that size function have reached the lowest temperature difference among the configuration which is 3.5%. This temperature difference did not exceed the limit that has been set which is 5% temperature difference. The final optimum meshing criteria with the selected functions sizes is shown in Fig. 6.

Simulation results: To compare between the recent simulation and the previous works, four reference points at the centre of each side of the channel are selected and shown as A, B, C and D in Fig. 7.

Smooth channel case: The simulation result for the case of smooth channel is Fig. 7 as temperature contours. The temperatures on the smooth channel blade is compared with the previously published results by Al-Kayiem and Ghanizadeh (2011) which are obtained by using analytical/finite difference coupled method.

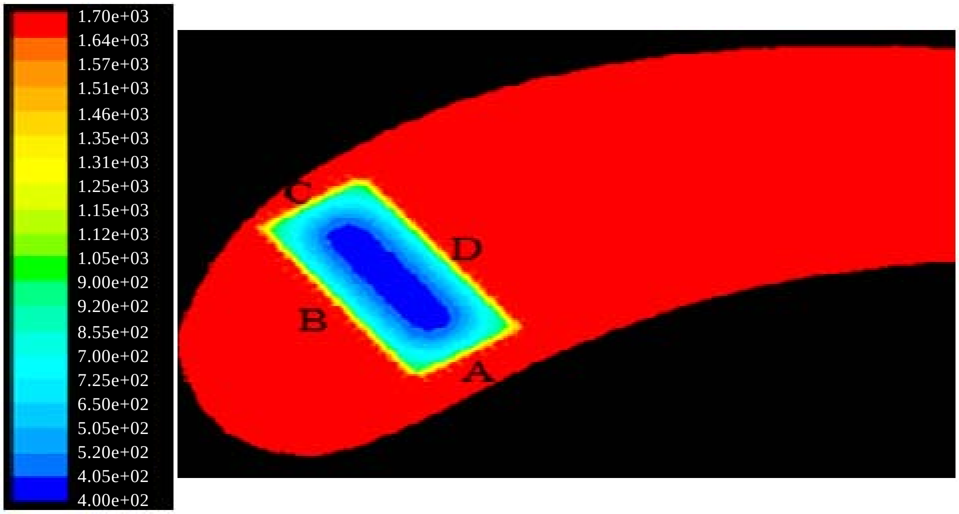

Fig. 7: Temperature at 4 points near smooth channel showed in FLUENT

Table 5: Comparison between analytical/FD solution and the recent simulation at blade root. (smooth channel case)

Point	Temperature (K) Incropera (2007)	Current study	Difference (%)
A	1504.5	1570.0	4.35
B	1530.0	1505.0	1.64
C	1506.0	1505.0	0.07
D	1432.0	1440.0	0.56

Table 6: Comparison between previous analytical/FD solution and the recent simulation, at blade root at height, H =157.5 mm (Smooth channel case)

Point	Temperature (K) Incropera (2007)	Current study	Difference (%)
A	1487.5	1635.0	9.92
B	1517.0	1635.0	7.78
C	1515.0	1635.0	7.92
D	1410.5	1635.0	15.92

Table 5 shows that the temperature difference between the results obtained from this study those by using the recent numerical method is less than 5% at the root of the blade.

However, that depends on the height of the blade. While at the third section of the height of the channel (H = 157.5 mm), as shown in Table 6, the temperature differences are bigger especially at point D which is located toward the tail of the blade. The temperature different is 15.92% at point D, while points A, B and C have differences less than 10% when comparing the two method.

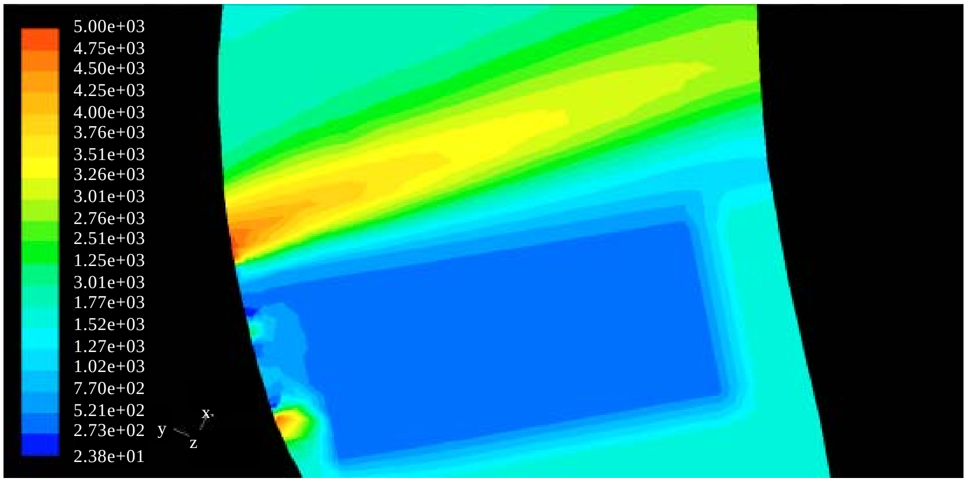

Fig. 8: Temperature distribution of 60 degrees rib

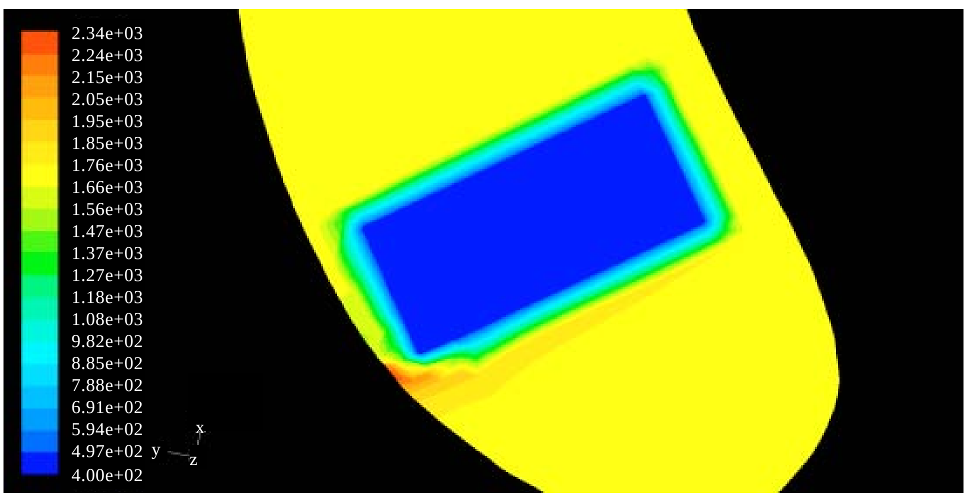

Fig. 9: Temperature distribution of smooth channel

Ribbed channel: Simulation for rib channel is carried out for the ribbed channel with rib angle $\alpha = 60°$, height-to-hydraulic-diameter ratio e/D = 0.078 and pitch-to-height ratio p/e = 8. Figure 8 shows the temperature distribution for a ribbed channel with ribs at 60 degrees. While Fig. 9 shows the temperature distribution in a smooth channel. However, Table 7 shows the temperature difference between the two findings.

To calculate the rib efficiency, the following equation is used:

$$\text{Reb efficiency} = \frac{T_{ribbed} - T_{smoot}}{T_{ribbed}} \times 100$$

Table 7: Temperature differences between smooth channel and rib channel

	Temperature (K)		
Channel type	Point A	Point B	Point C
Smooth	1660.8	1660.8	1660.8
Ribbed	1516.6	1516.6	1516.6

The contribution of the ribs to enhance the cooling performance is the mean of the three points, A, B and C. based on equation, the ribbed channels have enhanced the cooling performance by 9.5%. Meaning to say that the ribs are able to reduce the blade temperature by 9.5% which is considerable reduction.

CONCLUSIONS

A numerical analysis has been carried out by using Gambit modelling and FLUENT simulation software. Gird independency test is performed to reduce the total number of cells in order to minimize the total time and load when running the simulation on fluent. The best size function for the channel is starting size of 0.9, growth rate of 3 and size limit of 1.8 with blade size function starting size of 1.8, growth rate of 3 and size limit of 3.

Comparison has been done on the smooth channel between analytical/numerical coupled method results and numerical method (ANSYS-FLUENT) results. The difference found is 4.35% at the root of the blade. Meanwhile, on the height of 157.5 mm, the temperature difference found is slightly higher, mostly less than 10% except at point D which has 15.92%. This may be due to the location which is located further behind and toward the tail of the blade.

Another comparison is carried out for the 60 degrees rib angle with pitch-to-height ratio, p/e = 8 and height-to-hydraulic-diameter, e/D = 0.078 with the smooth channel. The results show that with the specified rib, the blade can be cooled by 9.5% compared to the smooth channel case.

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