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Numerical Investigation of Heat Transfer Enhancement in Ribbed Elliptical Passage

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Abstract: This study presents a numerical investigation for heat transfer enhancement and fluid flow in elliptical and circular passages equipped with circular ribs having triangular cross section. Boundary conditions are inlet coolant air temperature is 300 K with Reynolds numbers (Re = 7901). The surrounding constant hot air temperatures was (673 K). The numerical simulations were done by using Software FLUENT Version 15 in this part, it was presented the effect of using circular ribs in circular and elliptical passage channel on the fluid flow and heat transfer characteristics. Ribs used with pitch-rib height of 10, circular passage of 36 mm internal diameter and elliptical passage of 46×26 mm, 1.5 mm passage thickness and 0.5 m long. The temperature, velocity distribution contours, cooling air temperature distribution at the passage centerline, the inner wall surface temperature of the duct and thermal performance factor, the turbulent Eddy dissipation and turbulent kinetic energy are presented in this study. Passage with ribs was the better case which leads to increase the coolant air temperature by 9.1% for circular passage and 5% for elliptical passage, the temperature at the exit of centerline passage is greater than the elliptical passage by 3.96%. The turbulent Eddy dissipation for ribbed circular passage be higher than for ribbed elliptical passage by 100%. The values of turbulent kinetic energy for ribbed circular passage be larger than that for elliptical passage by 300% at the exist. The enhancement performance factor for ribbed circular passage be higher than that for elliptical one 120%. The higher friction factor ratio was found for elliptical cross section passage with ribs. Circular cross section with ribs is the best result (lower pressure drop and higher heat transfer enhancement).

Key words: Heat transfer, enhancement, internal cooling, gas turbine, rib, turbulator cooling

INTRODUCTION

Heat transfer augmentation is a substantial field of engineering, since because it enhances the heat exchangers effectiveness. Suitable techniques of heat transfer enhancement do benefit technical advantages and cost savings. There are different available techniques like heat exchangers, industrial processes and solar heater, Bergles (1998) specified many different techniques which can be divided into two groupings: ‘Passive’ and ‘Active’. Passive appoints special surface geometries such as coated surfaces and rough surfaces. While the active techniques need external power sources such as mechanical aids as indicated by Webb *et al*.

Metzger and Sham (1986) studied heat transfer effects around smooth rectangular channels with sharp, 180° turns. Carlomagno (1996) reported heat transfer measurements performed by means of infrared thermography in an internal flow through a 180° turn in a square channel which is relevant to the internal cooling of gas turbine blades. He showed that the Nusselt number increased ahead of the bend while some very high heat transfer coefficient regions were present at the wall towards the partition wall axis.

Liu *et al*. (2017) discovered that rounded cylindrical ribs have a big advantage over the classical ribs in both heat transfer enhancement and minimizing pressure loss. So, cylindrical ribs can increase the flow impingement at the upstream of the ribs which will increase the heat transfer areas. The design of groove and rounded cylindrical ribs will be an important way to enhance heat transfer and then overall thermal performance of internal channels.

Parkpoom and Paranee (2017) studied the heat transfer enhancement in a case of heat exchanger by supplying inclined baffles to generate vortex of co-rotating flow using the CFD method with the k-ε model. The circulating fluid is air which is flowing in a rectangular passage with height of 30 mm and the range of Reynolds number of 12000-35000. The CFD experiment presented a smooth channel and baffles channel (ratios of

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baffle-to channel-height at 0.1, 0.2 and 0.3 and the attack angle of 30°, 45° and 60°). Researchers discovered that (Nu and f) are concerned in a range of -10 to +10%.

Altaie *et al.* (2014, 2015a-c), Rashid *et al.* (2014) presented an experimental and numerical investigation of heat transfer characteristics and thermal performance in 50 cm stainless steel tube long, inside diameter of (30 mm) and outside diameter of (60 mm) with uniform surrounding hot air temperature of 1000, 1200 and 1400 K using ANSYS FLUENT 14.5. Results indicate that using internal ribs increase the heat transfer rate and having the highest performance factors for the case of turbulent flow.

In this study, the effect of using circular ribs in circular and elliptical cross section passages with internal flow and uniform wall surface temperature will be investigated.

MATERIALS AND METHODS

Governing equations: The continuity equation represents the conservation of mass may be written as (David, 1995):

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad (1)$$

ρ, represents air density, the velocity of fluid at selected point in the fluid flow-field may be represented by velocity components u, v and w at (x, y and z), respectively.

It is impossible to model the turbulent eddies in the fluid flow by direct numerical simulation with the availability of computer resources. The Cartesian tensor equation for the RANS equations is described as (Je-Chin *et al.*, 2000; Bredberg, 2002; Liou and Hwang, 1992):

$$\frac{\partial u}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right]+\frac{\partial}{\partial x_j}\left(\overline{\rho u_i' u_j'}\right) \quad (2)$$

If the hot surface temperature of T_h on one side and T_c on the other side, the heat transfer rate equation due to conduction is:

$$Q = UA\left(T_h - T_c\right) \quad (3)$$

From the Nusselt number definition, the Nusselt number of heat transfer may be calculated from:

$$h=\frac{Nuk}{L_c} \quad (4)$$

where, L_c is the characteristic length (or hydraulic diameter, D_h) can be written as:

$$D_h=\frac{4A}{P_W} \quad (5)$$

The Reynolds number of fluid flow is expressed as:

$$Re=\frac{\rho u D_h}{\mu} \quad (6)$$

RESULTS AND DISCUSSION

In the present research, results were obtained for elliptical passage compared with circular cross section passage as shown in Fig. 1a, b.

Figure 2 and 4 show contours of temperature distribution for smooth circular and elliptical cross section, respectively with surrounding hot air temperature of (673 K), inlet air temperature (300 K) and coolant air flow Reynolds number (Re = 7901). It was shown that the cooling air temperature at passage centerline remained constant throughout the channel while the coolant air temperature was affected near the wall for the presence of ribs for ribbed circular and elliptical cross section as shown in Fig. 3 and 5, respectively. This is due to the effect of circulation generated by the ribs themselves which clearly enhances the transfer of heat between the hot passage walls and the coolant airflow stream.

Figure 6 and 7 show contours of temperature distribution for the circular and elliptical cross section passages, respectively with circular ribs having triangular cross section at each rib location. It can be noted that after the first rib, air accelerates around the rib and boundary layer flow with separation is observed downstream of ribs which lead to make vortices and then enhances the heat transfer.

Figure 8 and 10 show contours of velocity distribution for smooth circular and elliptical cross section, respectively, the cooling air velocity at channel centerline decreased downstream constant throughout the channel while Fig. 9 and 11 present the velocity distribution contour through a circular and elliptical cross section with ribs, respectively, the coolant air flow was accelerated and decelerated through the passages, due to contraction and expansion for using these ribs.

The behavior of the turbulence Eddy dissipation (ε) for smooth circular and elliptical cross section can be seen in Fig. 12 and 14, respectively, its value be large only at the entering while for ribbed circular and elliptical passages, the turbulent Eddy dissipation is stimulate at each rib location as shown in Fig. 13 and 15, respectively. The turbulent Eddy dissipation for ribbed circular passage be higher than for ribbed elliptical passage by 100% as shown in Fig. 16-21.

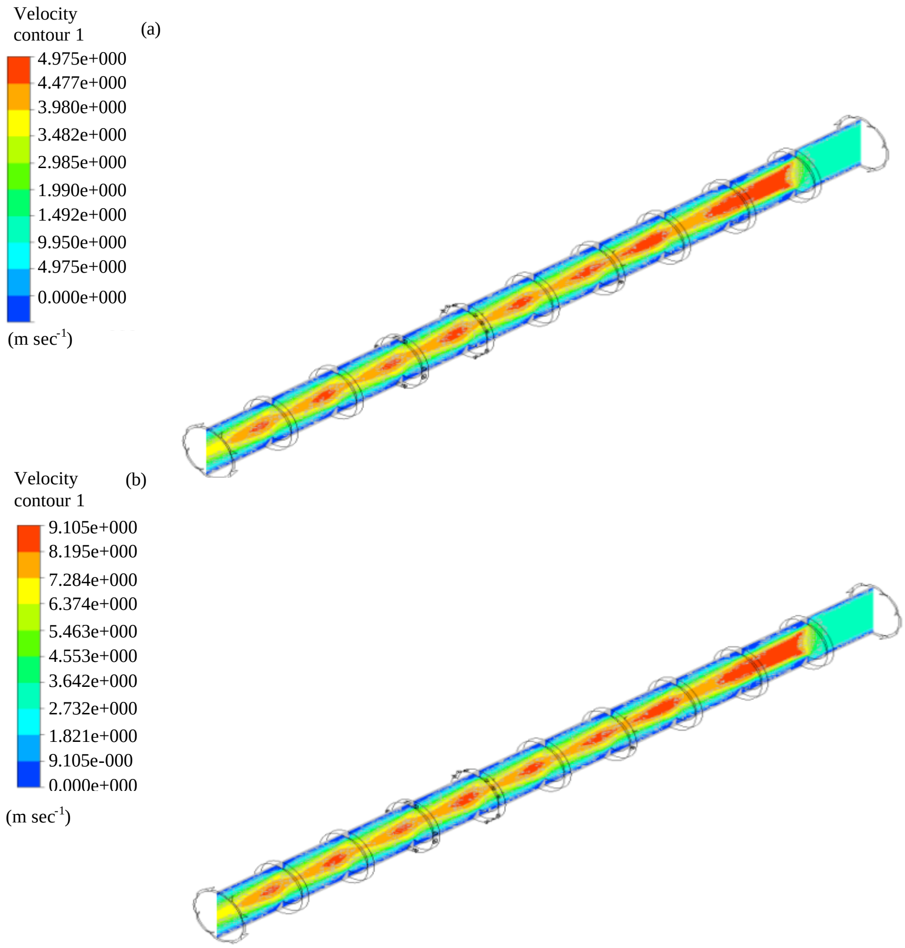

Fig. 1: 3-dimensional view of ribbed passage: a) Circular and b) Elliptical

Fig. 2: Temperature distribution for smooth circular passage

The turbulence kinetic energy (k) can be defined as the variance of the fluctuations in velocity in dimensions of m^2/sec^2. Figure 16 and 18 present the turbulent kinetic energy for smooth circular and elliptical cross section, its values be unchanged along the passage while its values be lower at the entering and maximized gradually along the passages, this behavior can be seen in Fig. 17 and 19. The values of turbulent kinetic energy for ribbed circular passage be larger than that for elliptical passage by 300% at the exist as shown in Fig. 22.

Figure 20 shows the cooling air temperatures at the passage centerline for circular and elliptical cross section passages at constant surrounding hot air temperature 673 K, inlet air temperature 300 K and coolant air flow of (Re = 7901). The coolant air temperature for ribbed

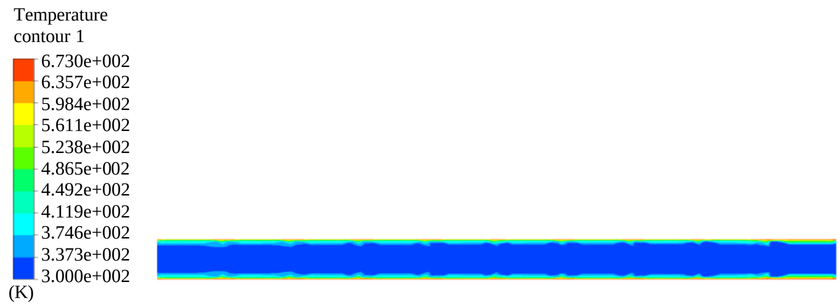

Fig. 3: Temperature distribution for ribbed circular passage

Fig. 4: Temperature distribution for smooth elliptical passage

Fig. 5: Temperature distribution for ribbed elliptical passage

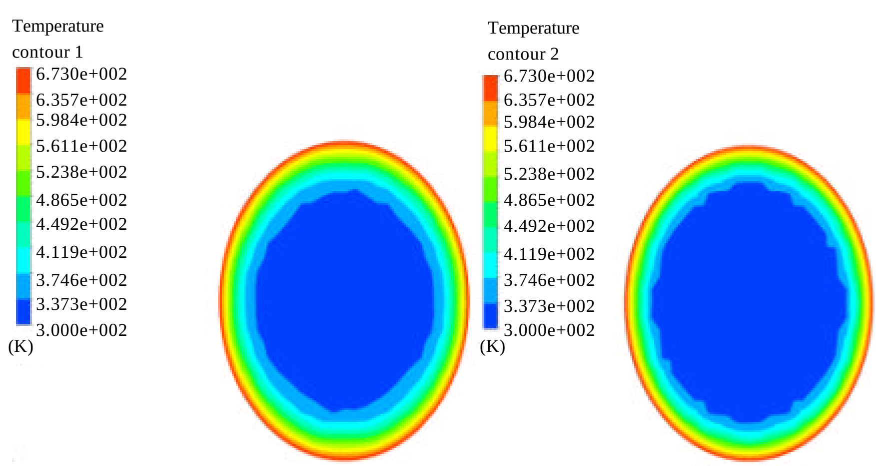

Fig. 6: Continue

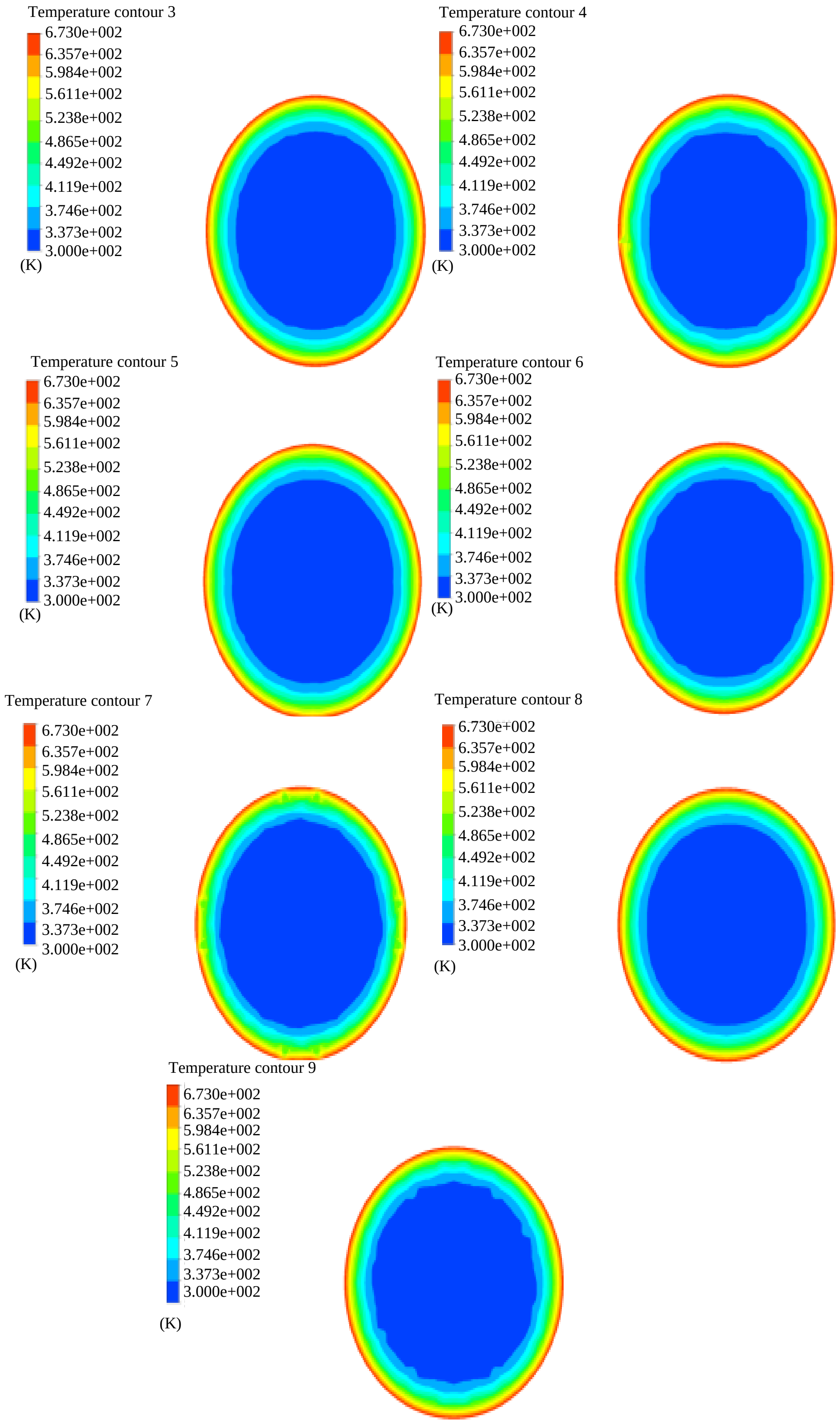

Fig. 6: Temperature distribution at each rib location for ribbed circular passage

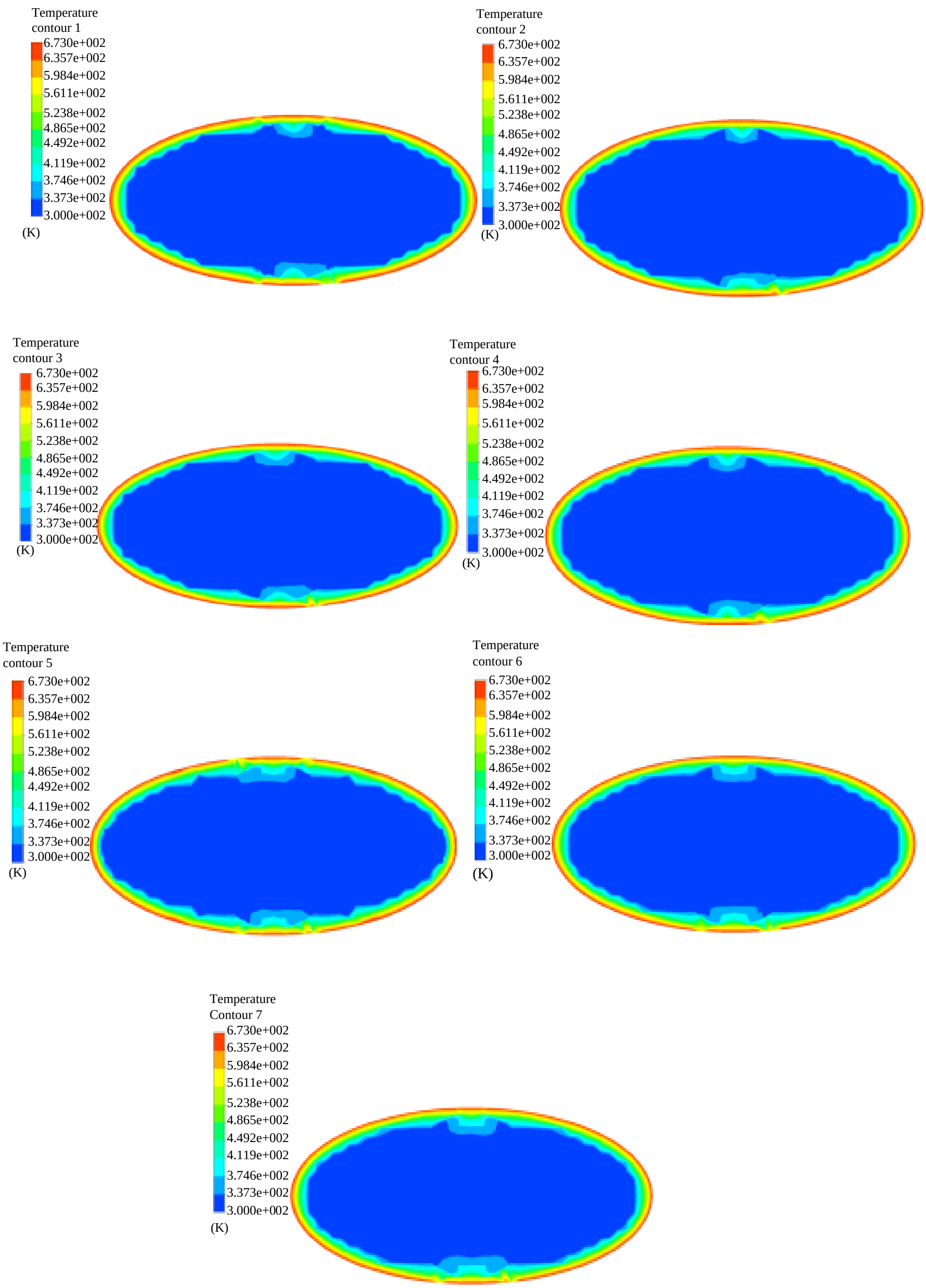

Fig. 7: Continue

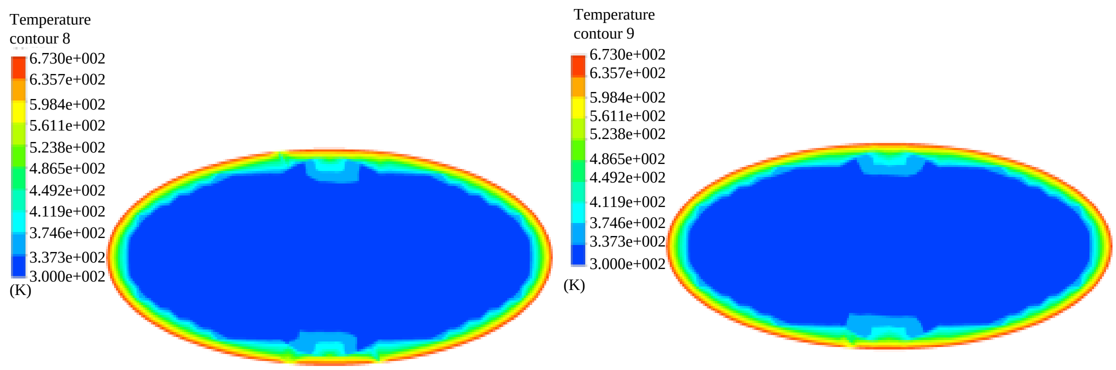

Fig. 7: Temperature distribution at each rib location for ribbed elliptical passage

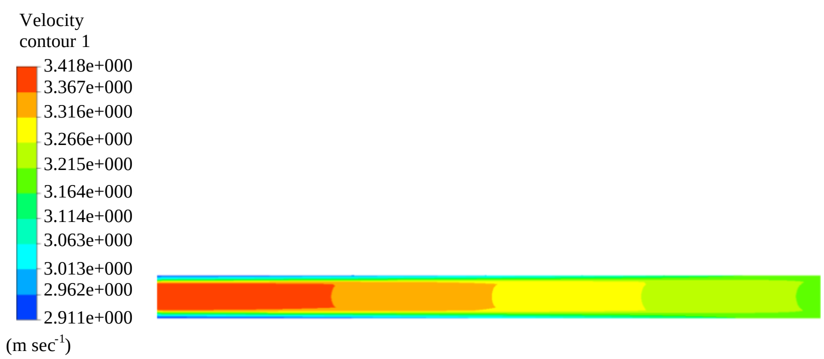

Fig. 8: Velocity distribution for smooth circular passage

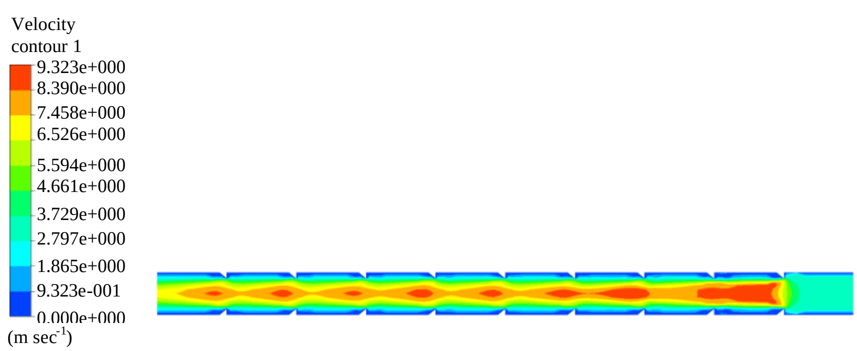

Fig. 9: Velocity distribution for ribbed circular passage

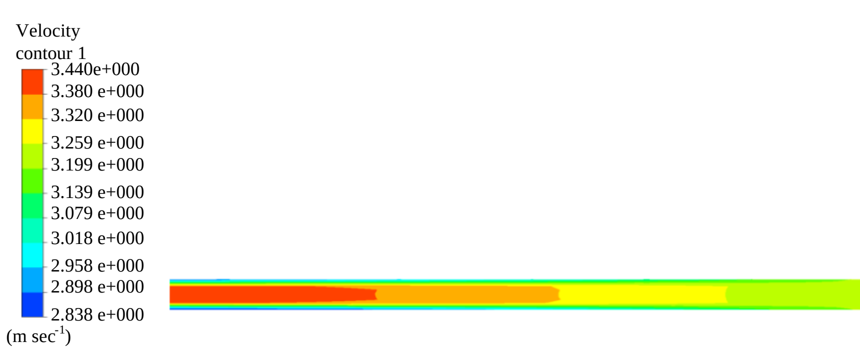

Fig. 10: Velocity distribution for smooth elliptical passage

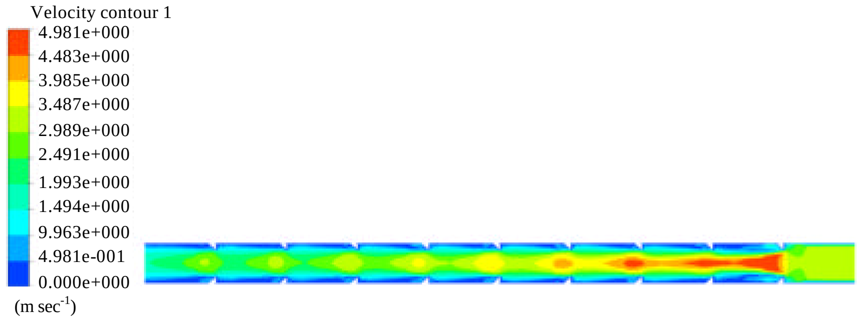

Fig. 11: Velocity distribution for ribbed elliptical passage

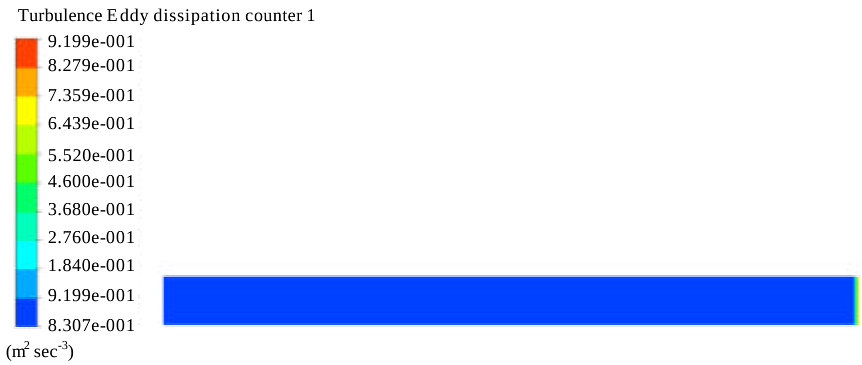

Fig. 12: Turbulent Eddy dissipation for smooth circular passage

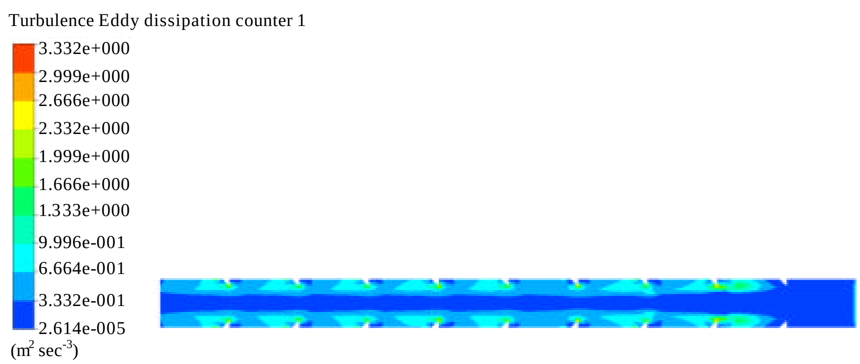

Fig. 13: Turbulent Eddy dissipation for ribbed circular passage

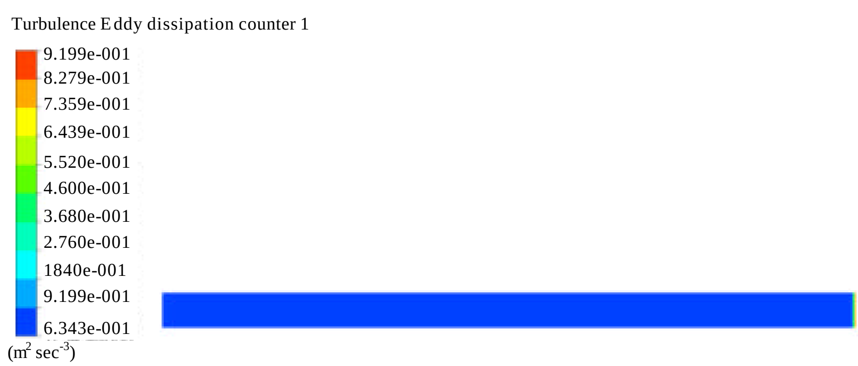

Fig. 14: Turbulent Eddy dissipation for smooth elliptical passage

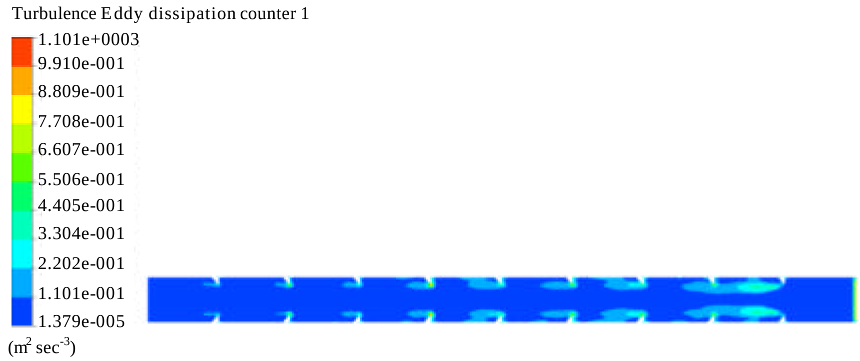

Fig. 15: Turbulent Eddy dissipation for ribbed elliptical passage

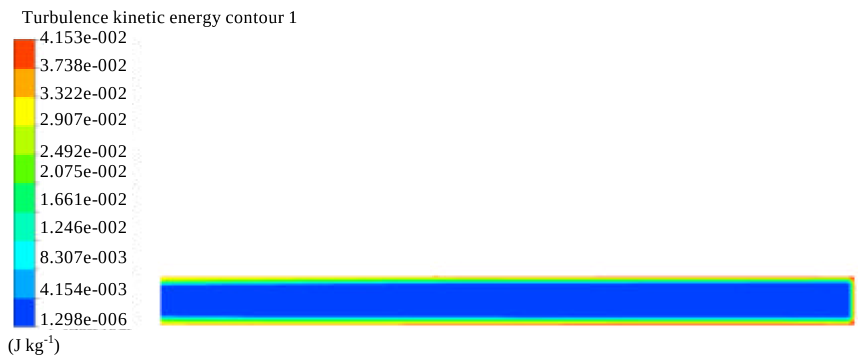

Fig. 16: Turbulent kinetic energy for smooth circular passage

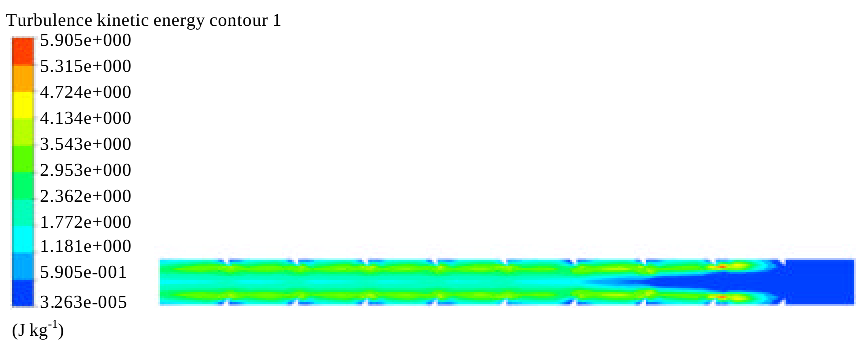

Fig. 17: Turbulent kinetic energy for ribbed circular passage

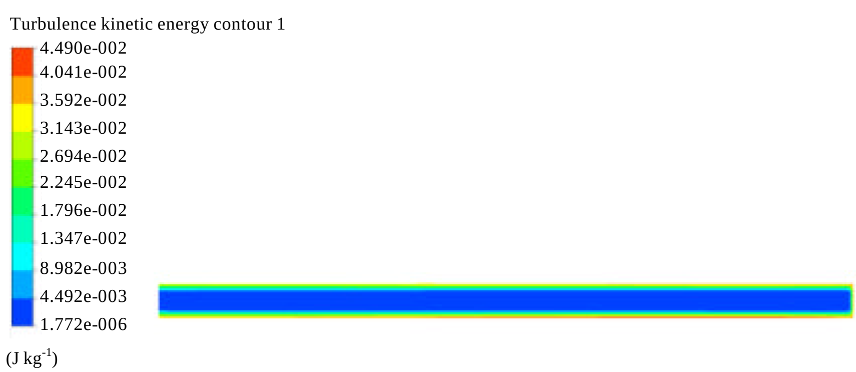

Fig. 18: Turbulent kinetic energy for smooth elliptical passage

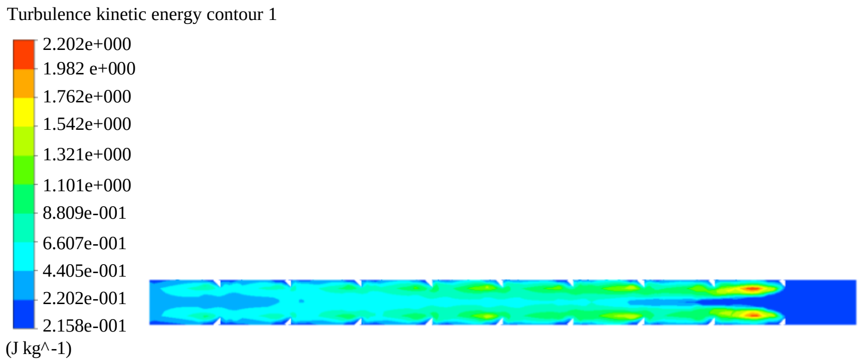

Fig. 19: Turbulent kinetic energy for ribbed elliptical passage

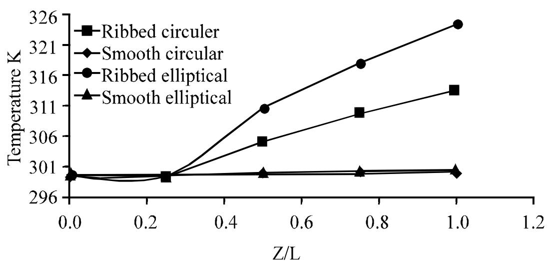

Fig. 20: Temperature distribution at passage centerline

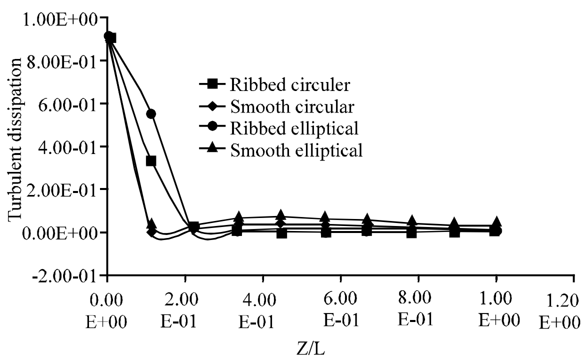

Fig. 21: Turbulent Eddy dissipation along the passages

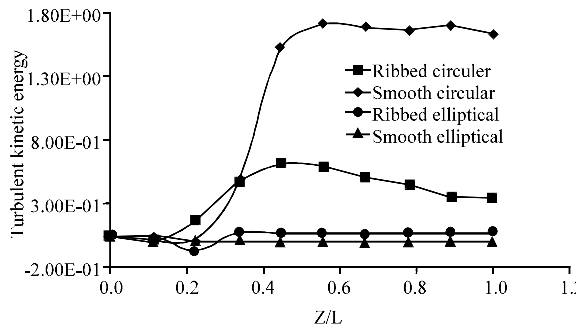

Fig. 22: Turbulent kinetic energy along the passages

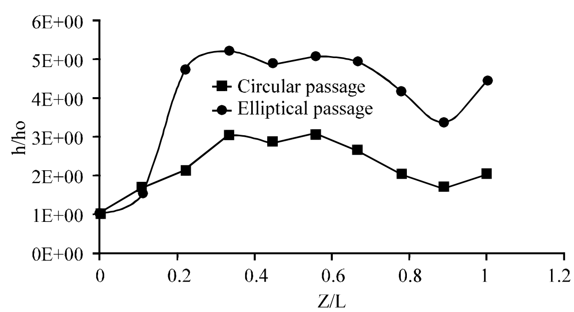

Fig. 23: Enhancement factor along the passages

passages be higher than that for smooth passages and temperature distribution at the circular passage centerline is higher than for elliptical by 3.96% (Fig. 21-23).

Figure 23 presents the thermal performance factor along the ribbed circular and elliptical passages, it can be seen that the thermal performance is larger than 1, this means that the ribs configuration performance always exceeds the smooth case. The enhancement performance factor for ribbed circular passage be higher than that for elliptical one (120%). This means that the heat transfer (cooling) in the ribbed circular is greater than the elliptical.

Figure 24 reveals the friction factor ratio (friction factor of ribbed passage divided by friction factor of smooth one) for circular and elliptical cross section with constant surrounding hot air temperature of (673 K) and flow Reynolds number of (7901). The higher friction factor ratio was found for elliptical cross section passage with ribs.

Figure 25 presents the compound thermal performance for circular and elliptical cross section with ribs at constant surrounding hot air temperature of 673 K and coolant air flow Reynolds number of Re = 7901. Circular cross section with ribs is the best result (lower pressure drop and higher heat transfer enhancement). This means the ribs cause more obstacle to the flow than enhancing the heat transfer.

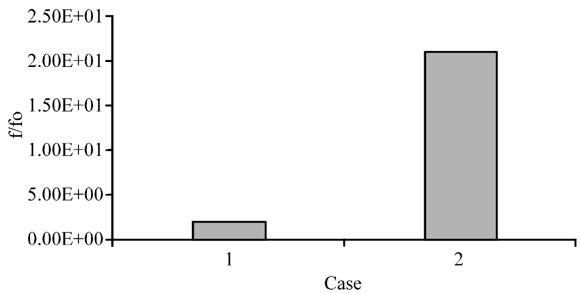

Fig. 24: Friction factor ratio for two cases; Case 1: Circular; Case 2: Elliptical

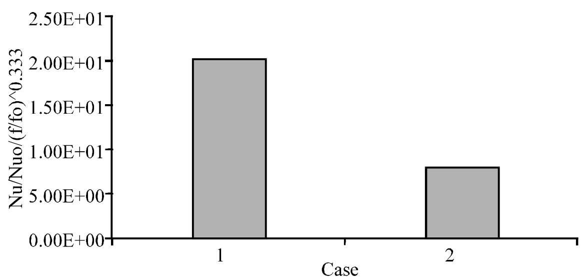

Fig. 25: Compound enhancement factor for two cases; Case 1: Circular; Case 2: Elliptical

CONCLUSION

The passage with ribs was the better case which leads to increase the coolant air temperature by 9.1% for circular passage and 5% for elliptical passage. The temperature at the exit of centerline passage is greater than the elliptical passage by 3.96%. The turbulent Eddy dissipation for ribbed circular passage be higher than for ribbed elliptical passage by 100%. The values of turbulent kinetic energy for ribbed circular passage be larger than that for elliptical passage by 300% at the exist. The enhancement performance factor for ribbed circular passage be higher than that for elliptical one 120%. The higher friction factor ratio was found for elliptical cross section passage with ribs and the circular cross section with ribs is the best result (lower pressure drop and higher heat transfer enhancement).

NOMENCLATURE

Symbol = Description (Units)
A = Surface area (m^2)
C_p = Air heat capacity (J/kg.K)
D_h = Hydraulic diameter (m)
e = Rib height (m)
f = Friction factor (-)
g = Acceleration due to gravity (m/sec^2)
H = Channel height (m)
h = Heat transfer coefficient (W/m^2.K)
k = Thermal conductivity (W/m.K)
L_c = Characteristic Length (m)
m. = Mass flow rate (kg/sec)
Nu = Nusselt Number (-)
μ = Air dynamic viscosity (N sec/m^2)
P = Rib spacing (pitch) (m)
Q = Rate of heat transfer (W)
pw = circumference (m)
Re = Reynolds number = $\rho uD/\mu$ (-)
T = Temperature (K)
u = Flow velocity (m/sec)

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