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Influence of Circular Perforated Ribs on Heat Transfer in Channel

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Abstract

This work investigates the influences of ribs and perforated ribs on heat transfer in square channels. The circular perforated rib was selected in this work. The study theoretically analyses parameters of the thermal performance, which includes Nusselt number, heat transfer rate, and air temperature distributions along the duct centreline for different loads and Reynolds numbers. The results indicated that by using the ribs in the channel, the heat transfer rate, heat transfer coefficient, and Nusselt number increased. The heat transfer rate, heat transfer coefficient, and Nusselt number also increase with using holes in ribs compared with that of the solid one. The reason for the increase in heat transfer is due to an increase in turbulence and thermal surface area. Moreover, it is observed changing shapes of the perforated ribs affect the parameters of heat transfer performance. The percentage of increase and improvement in heat transfer for solid ribs was (11.11%, 14.4%, and 12.5%) respectively. As for perforated ribs, the percentages of Nusselt number, convection coefficient, and heat transfer rate improved by (16.9%, 19.7%, and 17.2%) respectively, to a Reynolds number of 32051.

Introduction

Thermal energy systems cannot keep up with the ever-increasing power demand without technological improvements in heat exchange procedures. High input temperatures (1200K-1700K) are worked by most thermal systems, especially gas turbine blades, to achieve better thermal efficiency. The turbine blade materials used, even when coated with thermal insulating layers, may fail when exposed to extreme temperatures for long periods. Hence, efficient cooling techniques are necessary.

Enhancement in raising turbine intake temperatures has substantial since the cooling of turbine blades was used. Air circulated through the internal tubes of the turbine blades to cool them [1]. Thermal energy collection, processing, and usage are essential in large-scale industrial, commercial, and residential activities. Key industrial applications need heat addition and removal. Forced convection is one of numerous heat transfer mechanisms. Many modifications have been developed to enhance forced convection heat transfer. The heat transfer with perforated rib arrays within internal channels has been used to enhance heat transfer in gas turbine blades. Han et al. [2] used various angled rib approaches to enhance heat transfer. These rib angles were 30, 45, 60, and 90. They found that angled ribs transfer heat better compared to perpendicular ribs. Afterward, Buchlin [3] studied the convective heat transfer using perforated ribs. They found that in the perforated turbulent tube, the local thermal enhancement factor is three times higher than in solid ribs. Wright et al. [4] dealt with a rectangular channel with rib angled at 45° to assess the thermal performance. They used one of the broad walls to put the rib placement, while the other, smooth and thin, was used to measure heat transfer coefficients. They examined using a rectangular channel with angled ribs and a ratio of 3:1. The results show that an increase in the side length leads to more enhancement in the heat performance. In addition to the difference in distances, it helps improve thermal performance. According to the study, the angled ribbed channel functioned better than the smooth one. Baraskar et al. [5] provided an experimental analysis of the fluid flow characteristics and properties of heat transfer of V-shaped ribs in channels. They changed the gaps between the ribs, and the rib spacing was from height (p/e) equals 10. Nusselt number and friction factor were found to reach maximum values 2.57 and 2.85 times, respectively, compared to the smooth duct. Eren et al. [6] worked on forced convection to examine the heat transfer using a rectangular channel with a perforated circular. Their main objective is to improve heat transfer by ribbed channels. According to their findings, the heat transfer from the channel of perforated ribs was 34.1% greater than that from the solid ribs. Pressure decreases and heat transfer in a square-cross-section convergent channel with V and W rib tabulators were investigated by Abraham et al. [7]. Their findings showed that the W ribs provided higher enhancement rates compared with that of the channels; of W ribs. Singh et al. [8] explored enhancing heat transfer utilizing a square channel with rib turbulators, and their goal was to enhance heat transfer and friction. The findings demonstrated that the ribs increased heat transfer and significantly decreased pressure. Alfarawi et al. [9] researched the utilization of hybrid ribs to enhance heat transfer. They discovered that the hybrid ribs outperformed the semi-circular and rectangular ribs after utilizing a hybrid rib design in a rectangular channel. They calculated the Reynolds number (Re) and the pitch-to-rib height ratio (P/e) based on the geometric design and structure. Analytical and experimental assessments were integrated by Al-Jibory et al. [10]. They improved heat transfer by using circular ribs in rectangular channels. To make the gas turbine blade more effective and cooler, the researcher opted to add ribs to it. The results showed that finned ribs decreased the inner wall's temperature by 6.15% while increasing the coolant air's temperature by 10.22%. Fluid flow and heat transfer for different types of rib-roughened rectangular ducts were investigated by Kore et al. [11]. The findings demonstrate the superior thermal performance of the boot-shaped rib. Perforated ribs in channels were employed by Liu et al. [12] to thoroughly investigate turbulent heat transfer in internal cooling tunnels. The study aimed to improve the thermal performance of rectangular channels by using 90° perforated ribs. When 90° perforated ribs were introduced, there was an approximate 12% to 24% increase in local heat transfer. Numerical computations combined with experimental testing in their paper. The findings indicated that perforated ribs could be a useful addition to many cooling systems as a means of enhancing thermal performance. The effects of rectangular channels with 90° perforated ribs on the fluid flow velocity and thermal performance within a circular tube were evaluated numerically Hammoodi et al. [13]. The cooling air's temperature increased by 6.25%, 12.5%, and 17.5%, respectively, due to the ribs inserted inside the tube in the first, second, and third cases. The tube with ribs had a 90% higher flow rate than the tube without ribs. In 2023, Javanmard et al. [14] examined and assessed the thermal-hydraulic capabilities of many perforated ribs. The used holes were straight, convergent, and divergent and the hole inclination angle (0°, 30°, and 45°), the relative height of the hole entry (0.2, 0.4, 0.6, and 0.8), and the variation in the orb's cross-sectional area are the three geometric aspects of the ribs. It was found that the thermal performance is greatly impacted by perforated ribs with various geometric configurations. According to the study, rib inclination angles were the most important component in improving heat transmission.

Continuous research has been ongoing on improving heat transfer using ribs, but the impact of various perforated shape rib forms has received less attention. Consequently, improving heat transfer can be accomplished by choosing different perforated rib shapes. Best heat transfer is the criterion for choosing this perforated material form. Therefore, the work aims to enhance the heat transfer inside the channel using circular perforated ribs in the same channel.

Calculation Part

The effect of the perforated ribs in circular channels on the heat transfer performance is investigated analytically. Circular perforated was selected to achieve this study. Figure (1) shows the geometry of the used channel with ribs in the channel. The used channel that has a length of channel 1300 mm, duct thickness of 1 mm, duct cross-section of 125 × 125 mm and outlet pipe diameter of 125 mm. The rib's cross-section is rectangular length of rib is 115 mm, thickness is 10 mm and spacing between ribs is 80 mm as shown in figure (1).

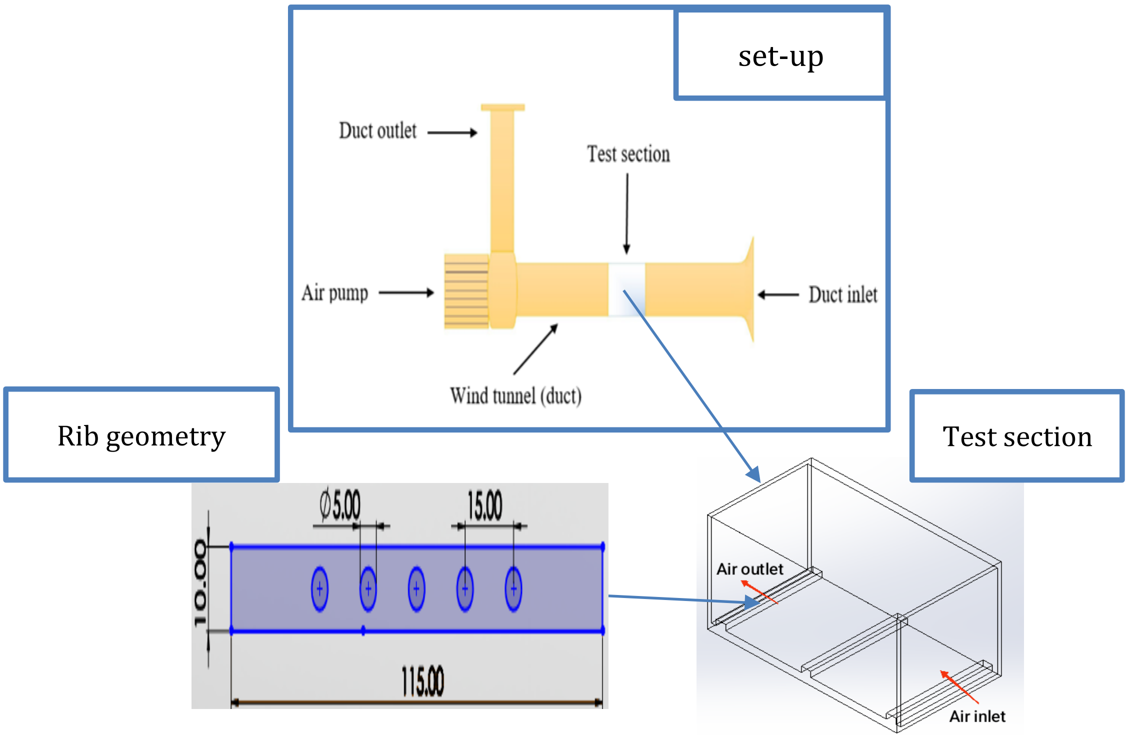

Fig. 1. Schematic view of the present set-up and perforated ribs [15].

The bottom channel is subjected to heat generation from an electronic source and is identified by the base. The inlet air is considered to be at ambient temperature. The ribbed channel iron was inserted into the acrylic test section and examined in its solid and perforated states. The perforated sections were examined after measuring the solid ribs. The hole is generally (5 mm) in diameter, (5) circular holes, and (10 mm) deep. The distance between the radii of the holes is (15 mm) and the perforation is along the cross-section of the ribs. As shown in the figure below. There were five holes distributed on each rib. Moreover, the different velocities of air are considered. The main characteristics and geometric information of a heat transfer investigation carried out on a ribbed channel or duct are shown in this table 1. The channel's ribs modify the flow dynamics and have an impact on the rates of heat transfer.

Table 1. Details of channel and test section used

Parameters	Value
Spacing of Ribs	80 mm
Velocity (u)	(1.5, 2 ,2.5 ,3 , 3.5, 4) m/s
Length of plate (l)	200 mm
Width of plate (w)	115 mm
Width of ribs (b)	10 mm
Length of ribs (a)	115 mm
Diameter circular hole	5 mm
Area of case no ribs (A_{p1})	23000 mm
Area of case solid ribs (A_{p2})	27050 mm
Area of case perforated ribs (A_{p3})	31173.34 mm

Information on equations: The main parameters of heat transfer, including Nusselt number, heat transfer coefficient, heat transfer rate, and temperature were evaluated using the following equations [15]:

$$\dot{Q}conv. = \frac{Q\,\dot{e}l - \dot{Q}loss}{A} \qquad (1)$$

The measured input power to the heater was denoted a Qel,s you can calculate its electrical heat input (P=IV), where I *is the current* and V *is the voltage*. We may express the convective heat transfer from the test portion as [13]:

$$\dot{Q}\text{conv} = \dot{m}\ \text{Cp}\ \Delta\text{T} \qquad (2)$$

The specific heat of the air and the mass flow rate of air ($\dot{m}$) are defined. It can be calculated the air mass that flowed through the ribs, around the ribs, by using the following equation [15]:

$$\dot{m} = \rho \text{VA} \qquad (3)$$

In this context, ρ and V *represent the air density and velocity*, respectively. A represents the area of the fluid that makes contact with the plate [12].

$$Q_{conv.} = h\ A\ \Delta T \qquad (4)$$

$\Delta T = T_s - T_m$, where T_m is the mean temperature andT_s is the temperature of the channel surface. The Nusslet number formula was [6] :

$$\text{Nu} = \frac{h\,D_h}{k} \qquad (5)$$

Here is where the sheet's *thermal conductivity* (k), the temperature gradient (ΔT), and the sheet's thickness (t) are defined**,** the area (A) calculation [6] [7]*:*

1. Case one without ribs

$$\text{A}_{\text{p1}} = l * w \qquad (6)$$

Where a: *length or side length, b: width,* A_{p1}: The area of the plate without ribs

2. Case two solid ribs

N*:* number of ribs

$$\text{A}_{\text{p2}} = \text{A}_{\text{p1}} + \text{N}[2(\text{b} * \text{b}) + 3(\text{b} * \text{a})] \qquad (7)$$

A_{p2} *:* The area of plate solid ribs

3. Case three perforated ribs (circular hole) [12]

$A_C = \frac{\pi * d^2}{4}$ (8)

Where d*: is the diameter of hole ribs,* λ *: number of holes* [15].

$A_{p3} = A_{p2} - 2(N * \lambda * A_C) + 2(N * \lambda * \pi * d * b)$ (9)

Lytle and Webb found that the lateral conduction was insignificant since the sheet was so thin [15]. The fluid Properties are calculated depending on inlet temperature [6].

$D_h = \frac{2(W * H)}{(W + H)}$ (10)

When, D_h *is the hydraulic channel diameter, the variables* A_d *and* P_d *denote the duct's perimeter* and cross-sectional area. In this study, a square-shaped duct was used. The Re is defined as [12]:

$Re = \frac{\rho\, u D_h}{\mu}$ (11)

ρ*:* represents the air density, u: the average flow velocity, D_h: the hydraulic channel diameter, and μ: the dynamic viscosity.

Results and Discussion

For channels no ribs (No_r)′ solid ribs (Sr)’, and perforated ribs (Pr)’, figure (2) displays the Nusselt number versus the Reynolds number. The figure illustrates how employing ‘Sr’ and ‘Pr’ significantly improves the Nusselt number. As the Reynolds number rises, the Nusselt number increases. Concerning other channel types, the channel featuring ‘Pr’ exhibited the highest Nusselt number, whereas the No_r channel lacking ribs demonstrated the lowest Nusselt number. For example using ‘Sr’ and ‘Pr’ channels increased the Reynolds number at 32,051 from 16.9% and 11.11%, respectively, compared to a channel ‘No_r’. This behaviour can be explained by the fact that the channel's surface area increases when ribs are added as compared to that when they are not. An additional parameter to consider may be raising the turbulence-causing Nusselt number of the ‘Pr’ in comparison to the ‘No_r’ channel. By adding holes to the ribs about the channel with ribs and ‘No_r’, the turbulent flow is increased. Furthermore, in comparison to the other shapes, the perforated ribs have the largest Nusselt number due to their larger surface area. ‘Pr’ also disrupts the boundary layer more effectively than No_r’or ‘Sr’, leading to higher Nusselt numbers and better heat transfer.

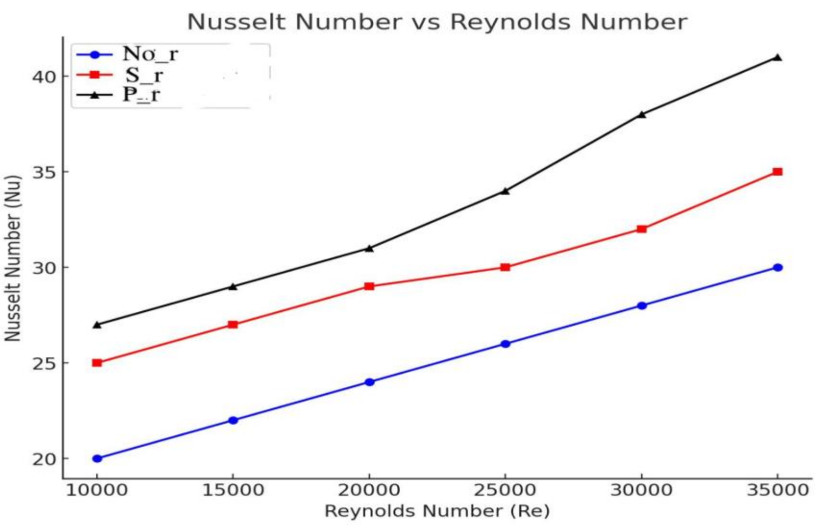

Fig. 2. Differences in Nusselt and Reynolds Numbers between the Three Rib Cases.

The heat convection coefficient for channels with or 'No_r', 'Sr' and 'Pr' channels is displayed with respect the Reynolds number as shown in Figure (3). The figure shows that, the heat transfer coefficient rises as the Reynolds number does for all cases. Furthermore, compared to 'No_r', the heat transfer coefficient rises when solid and perforated ribs are used. For instance, at a Reynolds number of about 32051, the heat transfer coefficient of 'Sr' is larger than of No_r as 19.7%. In the meantime, the 'Sr' heat transfer coefficient rises by 14.4%. This behaviour makes sense because adding ribs increase the channel's surface area. Furthermore, the perforated ribs caused the flow inside the channel to become more turbulent i.e. increasing the heat transfer coefficient. These results were consistent with previous studies such as Javanmard et al. [14] and Hammoodi et al. [13].

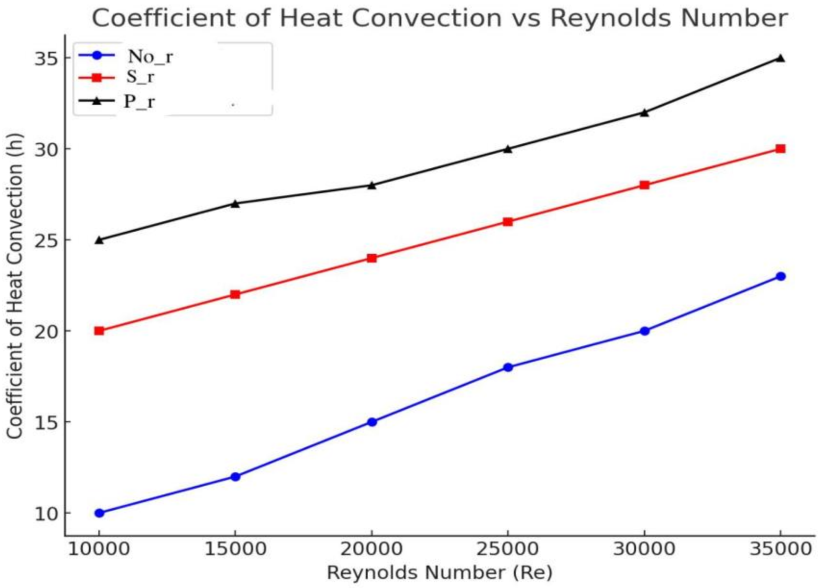

Fig. 3. Differences in coefficient of heat convection and Reynolds Number between the three rib cases and the no ribs model.

At figure (4), the heat transfer rate (Q) as a function of with Reynolds number (Re) for three different configurations in a square channel for all three previous cases is displayed. The data covers Reynolds numbers from 12,000 to 32,051. For all cases, the heat transfer rate (Q) increases slightly as the Reynolds number rises. This makes sense because faster fluid flow is frequently linked to higher Reynolds numbers, which enhance convective heat transfer. It can also be seen that using 'Pr' and 'Sr' in channels improves heat transfer dissipation in comparison to channels 'No_r', which were around 17.2% and 12.5%, respectively, at Reynolds numbers of 32051. This can be attributed to an increase in the rib surface area that led to an increase in heat transfer.

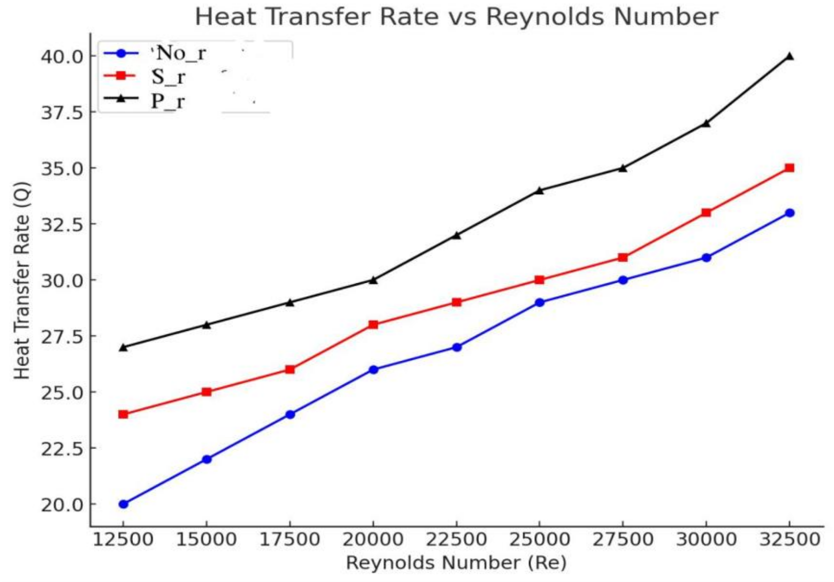

Fig. 4. Differences in total heat flow and Reynolds Number between the rib Cases.

Conclusions

The current investigation comes to the following conclusions:

1. The heat dissipation is increased by adding ribs to the channel compared to that without ribs.
2. The performance of the perforated ribbed channel is consistently better than the channel with ribs due to an increase in the surface area and turbulence.
3. The heat transfer coefficient and heat dissipation of the perforated ribs gave the highest value compared to the ribs beside the channel without ribs.
4. According to the study, the performance of heat transfer may be significantly increased by adding ribs to the channel. Moreover, perforated ribs are more a useful way to increase the heat transfer coefficient.

5- For solid ribs, the corresponding percentages of improvement and increase in heat transfer were 11.1%, 14.4%, and 12.5%. Concerning perforated ribs, the percentages of heat transfer rate, convection coefficient, and Nusselt number increased to 32051 (respectively, 16.9%, 19.7%, and 17.2%).

Nomenclature

A	Surface area (mm^2)
a	length of ribs (mm)
b	width of ribs(mm
Cp	Specific heat at constant pressure, J/kg. K
D_h	Hydraulic diameter of the duct, m
e	Rib height, m
H	Test duct height, m
h	Heat transfer coefficient, $W/m^2.K$
L	Test-section length, m
l	length of plate (mm)
m	Air mass flow rate, kg/s
Nu	Nusselt Number
N	number of ribs
p	Rib pitch, m
P	Pressure, Pa
q"	Net heat flux, W/m^2
Re	Renold Number
T	Temperature, K
U	Flow mean velocity, m/s
W	Test-duct width, m
w	Width of plate (mm)
p_r	perforated ribs
S_r	Solid ribs
No_r	number of ribs

Greek symbols

ρ	density of the fluid (kg/m^3)
μ	the dynamic viscosity(Pa.s)
f	friction factor
λ	number of hole
€	the side length

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