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Research Article

Experimental investigation of thermo-hydraulic performance of multi semicircular rib of dimple hybrid channel

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ABSTRACT

To enhance the performance of gas turbine, it is necessary to operate at high inlet gas temperature, which required more effective cooling method for turbine blades. The ribs, protrusion and dimples are efficient turbulators for heat transfer augmentation. In the present study new compound structure of multi semicircular rib-dimple are presented experimentally and validated with simulation/optimization techniques to achieve pressure drop and heat transfer characteristics. Multi semicircular rib with 10 and 20 dimples are investigated and placed at the bottom surface of a rectangular channel. The experiment was conducted by considering the data such as: Reynolds numbers (Re) 12,000 to 30,000, Rib pitch (P) to height (e) ratio = 8 to 10, rib height (e) to channel hydraulic diameter (Dh) ratio = 0.15 and dimple depth (δ) to dimple diameter (d) ratio = 0.2. It is found that the combination of multi semicircular rib with 20 dimples shows the maximum thermal performance over multi semicircular rib with 10 dimples and rib alone channel. Friction loss found more in compound channel with 20 dimples whereas less in the 10 dimples. Compound channel with 20 dimples enhanced 30 % more heat transfer over 10 dimples and 25 % additional than the rib alone channel, also multi semicircular rib shows the least thermal performance.

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INTRODUCTION

To get more output and efficiency from a gas turbine; it should operates at very high inlet gas temperature. These temperatures are not sustained by blade material. To protect the blade life; various cooling techniques are used; the internal cooling method involves protrusion, dimple, ribs, fin, vortex generator and groove. Rib turbulators and dimple alone are frequently used in the gas turbine blade cooling or other cooling applications. These methods are useful to generate recirculation, vortices, separation of

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flow and attachment/reattachment in the flow channel that enhanced the involvement of fluid molecules and consecutively heat transfer rate.

In the early years; many researchers focused on different types of rib geometries. J. C. Han [1] reported parallel and V-shaped broken ribs and shows that the 60^0 parallel or V-shaped broken ribs indicates more heat transfer enhancement than the 45^0 parallel or V-shaped broken ribs. Jongmyung Park et al. [2] numerically presented 45 deg. angled rib for flow structural at Reynolds number from 18300 to 48000. Some studies show that due to angled rib turbulators large-scale secondary flow induced also mixing of flow develops, which increased the local Nusselt numbers. Patil and Borse [3] focused on various cooling techniques for gas turbine blade, concluded that there is still scope to use W Shape, Semicircular and Multi Semicircular shape ribs. Luca Baggetta et al. [4] studied 450 angled ribs using the liquid crystal thermography and show that existence of intersecting rib, percentage rate of heat transfer enhancement was less than the pressure drop. Abraham and Vedula [5] presented V and W rib for converging channel at Reynolds number ranging from 5000 to 30000 and found same average Nusselt number of V and W shape ribs. Promvonge and Thianpong [6] experimentally presented rectangular, triangular and wedge shapes ribs at staggered and in-line arrangement, shows triangular rib with staggered arrangement performed well over the other ribs. Jae-Won Seo et al. [7] presented optimization of a boot-shaped rib at Reynolds number 20,000 using 3-dimensional RANS analysis and MOGA techniques. Concluded that the heat transfer oriented design shows more FNu and Ff than to the friction factor oriented design. Min Kim et al. [8] presented an optimal design to find out appropriate rib geometry of angled rib using advanced response surface method. Observed the maximum thermal performance at rib angle (α) - 54.670 deg. and pitch ratio (P/e) - 6.8.

In some another cooling technique, dimples are used for heat transfer enhancement due to less pressure drop advantage. Yu Rao [9]studied various shapes of dimple such as: spherical, teardrop, elliptical and inclined elliptical at Reynolds number 8500-60,000. Result shows that the teardrop dimples performed well against regular spherical dimples; also the elliptical dimples indicate lowest performance than the spherical dimples. Lu Zheng et al. [10]studied ridged dimple and show that reduction in the wall temperature and enhanced the heat transfer. Saeed Nazari et al. [11] studied staggered, square and triangular arrangement of dimples by taking three depths of dimples: (δ/d = 0.25, 0.375 and 0.5). Result indicates that dimple depth ratio (δ/d) = 0.25 which shows the superior performance than other tested depth ratio. Also staggered and triangular arrangement of dimple performed well at low and high dimple depth. Ayush Gupta et al. [12] studied the performance of plate heat sink using dimples and protrusions. Show that maximum performance of heat sink observed at a staggered arrangement when dimple pitch ratio (s/d) kept 2.5 and dimple depth ratio 0.5.

To fulfil the today's industry need and also to achieve more enhancement from cooling techniques; researchers are focused on combination of two ribs (hybrid structure), Sahu et al. [13] focused on hybrid ribs, which is combination of triangular and semicircular ribs. The rib pitch to height ratio (p/e) kept 6.6 to 53.3 and Reynolds number from 12,640 to 52,410, they show that hybrid rib performance was highest at pitch ratio of 13.3. Pongjet Promvonge et al. [14] presented combination of chamfered-V-groove and punched-V-rib for solar air heater duct. Range of Reynolds number (Re) varies from 5300 to 23,000. It indicates that the combined punched-V-rib and chamfered-V groove shows 14-15% more performance compared to chamfered-V-groove and combined solid-V-rib. Qi Jing et al. [15] studied different dimple/protrusion arrangements at Reynolds number 10,000 to 100,000 concluded that protrusion produced the largest Nu compared with dimple, also performance of combined dimple–protrusion was found in between dimple and protrusion alone case.

Nowadays, few researchers focused on combination of two methods for cooling the gas turbine blades, such as ribs with protrusions, pin fin with dimples, ribs with dimples and dimples with protrusions. Patil et al. [16] presented compound and rib alone channel for gas turbine cooling, indicated that W rib compound channel shows improved performance than W rib channel. Yonghui Xie et al. [17] studied numerically hybrid structure of dimple with secondary protrusions, different configurations of dimple-protrusion was tested and concluded that dimple channel with secondary protrusions shows higher thermal performance than ordinary dimple channel. Also Xie studied combination of two techniques such as: pin-fin-dimple/protrusion, dimple/protrusion structure in a U shaped duct. It shows that the pin fin-dimple/protrusion structure enhanced more heat transfer than the dimple/protrusion structure [18]. Rao and Zhang [19] presented experimentally combination of miniature V-shaped rib with dimple at Reynolds number (Re.) up to 60,000 indicated that the hybrid structure shows more heat transfer enhancement than the dimple structure. Inderjot Kaur and Prashant Singh [20] studied combination of V-shaped protrusion/concavity with miniature V-rib. Concluded that the hybrid structure of V-rib with V-protrusion shows the improved thermal hydraulic performance (THP) of range 2.15.

In literature, major work was found on mainly the dimples or ribs alone, only some investigators studied combination of different shape of ribs or two different methods such as hybrid structure, rib-dimple, rib-protrusion, dimple-protrusion [16,19]. The aim of the existing study is to develop advanced cooling technique for gas turbine blade, which is substantially the combination of two different enhancement techniques. In the present work mostly focused on combination of multi semicircular shape ribs with spherical dimples for thermal performance, also Multi semicircular rib alone and compound channel with 10 and

20 dimples are presented to get optimal configuration of ribs with dimple pattern.

Combustion turbines, also referred to as gas turbines, are a kind of internal combustion engine that produces mechanical energy from liquid fuels like natural gas [21]. Usually, an electric generator or other machinery such as ships, airplanes, and other vehicles are powered by this mechanical energy. The compressor, the combustion chamber, and the turbine are the three primary parts that make up a gas turbine's basic mechanism [22]. The compressor takes in ambient air and compresses it to a high pressure to start the operation. In order to get the air ready for combustion, this stage raises its temperature and pressure. Axial-flow compressors, which have several stages of moving and stationary blades, are used in modern gas turbines to get great compression efficiency. After entering the combustion chamber, the high-pressure air from the compressor is combined with fuel and ignited. The generated gas's temperature and pressure are greatly increased during the combustion process, and the chamber's construction allows it to withstand extremely high temperatures and steady combustion. There are several different kinds of gas turbines, such as microturbines, aeroderivative gas turbines, and heavy-duty gas turbines. Heavy-duty gas turbines are built to run continuously under heavy loads and are commonly seen in power plants that generate electricity. Smaller power plants and mechanical drive applications, including powering compressors or pumps, employ aeroderivative gas turbines, which are evolved from jet engines. Compared to heavy-duty turbines, they are more flexible and lighter. Due to their tiny size and excellent efficiency, microturbines are small-scale turbines that are utilized in combined heat and power (CHP) and distributed generation systems.

EXPERIMENTATION

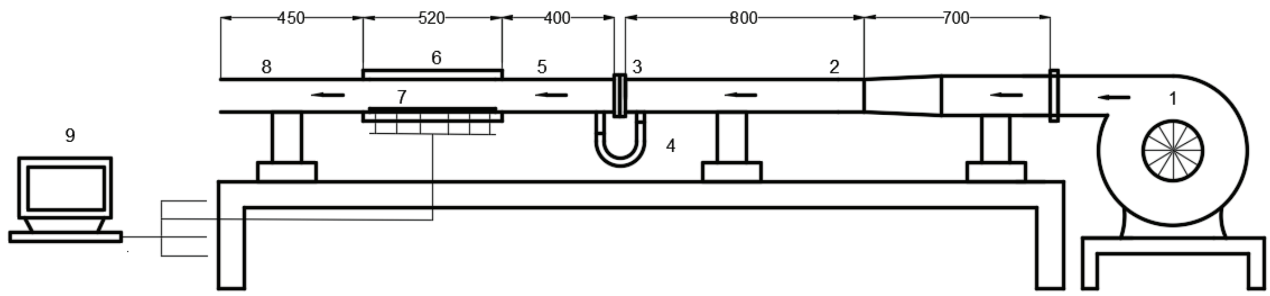
Experimental Detail and Methodology

An experimental set up was designed and manufactured to measure the pressure loss and heat transfer in multi semicircular rib and compound channel, as shown in Figure 1. Main parts of the set up was a centrifugal blower, entrance/developing section, an orifice plate assembly, rectangular duct with test section and exit section. To prevent the heat loss from the rectangular channel, it was made from Bakelite sheet and the entire length of set up was 2900 mm, out of that 1200 mm - entrance section, 520 mm - test region and 450 mm - exit region. The aspect ratio and hydraulic diameter of channel was 4:1 and 36 mm respectively. In the experimental set up a blower was connected to 700 mm flow developing region after that entrance section attached to ensure fully developed flow in the rectangular channel then after test section assembly connected. Lastly the exit section was connected to the rectangular duct to decrease the end effects of flow.

Air mass flow rate was adjusted through variable frequency drive (VFD) and measured with an orifice plate assembly. The mica flat plate heater was used to supply uniform heat flux and controlled through voltage variable of 6 Amperes rating. Pressure loss in the test section was recorded using digital micro manometer connected along the inlet and outlet pressure taps. Inlet and outlet temperature of air was recorded using the thermocouples placed at respective sections. Also the surface temperatures of test plate are recorded using K-type thermocouples inserted at various locations of test surface and output of thermocouples are connected to the data acquisition system. All instruments was calibrated from NBL accredited Laboratory and at steady state condition all experimental data was recorded, Figure 2 shows the photo graphs of experimental set up.

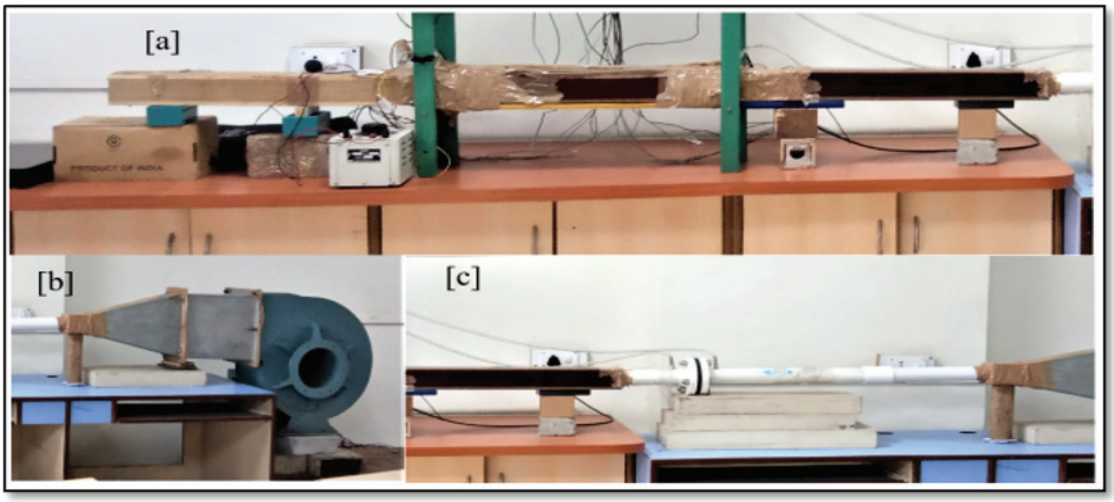
Test Section

For test plate 12 mm aluminum sheet was used and the multi semicircular ribs are pasted on the surface of test plate using adhesive material. Dimples on test plate surface are carved using a special designed ball nose tool of diameter 20 mm and depth of dimple kept 4 mm (δ/D - 0.2).The mica flat plate heater was used to supply a constant heat input and placed between the base plate and a test plate. To reduce the heat loss from the channel, proper glass wool



1- Centrifugal blower 2 - developing/straighten section 3 - orifice plate assembly 4 - U tube manometer 5 - Inlet region 6- rectangular duct 7- Test plate 8 - exit region 9 - data acquisition system

Figure 1. Schematic representation of experimental setup.



a- Rect. duct with exit section, b- Blower with honey comb section, c- Inlet section and developing section with orifice plate

Figure 2. Experimental set up.

insulation was provided between heater and base plate. The test plate with base plate and heater are bolted and placed in a bakelite made rectangular channel. Figure 3 shows the photographs of rectangular duct with different test sections.

Rib Geometry

The multi semi-circular shape rib was made from 45 mm diameter aluminum pipe, first outer and inner diameter of 3003 aluminium pipe was prepared on CNC machine, then using special purpose machine required size ribs are prepared. Rib width and height was kept 5 mm each, rib height to hydraulic diameter ratio (blockage ratio ,e/Dh) of the rectangular duct was 0.150 and pitch to height ratio of rib (P/e) was 10 to 12. Special ball nose tool of 20 mm diameter was designed for dimples and carved on the test plate surface by coordinate-measuring machine

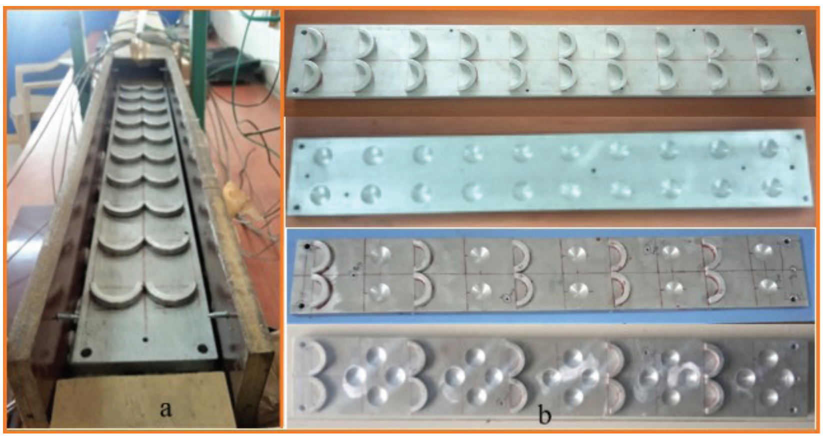


Figure 3. Rectangular channel with different test plates.

Table 1. Multi semicircular rib-dimple pattern for cooling application

Cases	Configuration	Number of ribs/dimples
1	Multi semicircular rib channel	10 ribs
2	Dimple channel	20 dimples
3	Multi semicircular rib - dimple compound channel	5 ribs + 10 dimples
4	Multi semicircular rib - dimple compound channel	5 ribs + 20 dimples

(CMM), also dimple depth to dimple print diameter ratio (δ/D) was kept 0.2. In this study multi semicircular rib and compound channel are tested at Reynolds number (Re) 12000 to 30000, for finding the best combination of multi semicircular rib-dimple pattern for cooling application as shown in Table 1.

Data Reduction

In the present work the values of heat transfer coefficient, Nusselt number and friction factor are determined by considering the measured experimental data[23]. The procedure to calculate the different parameters is given below: The Reynolds number (Re) is obtained from equation (1) recommended by Promvonge and Thianpong (2008), where μ - dynamic viscosity of fluid (air) and V - velocity of air passing through duct.

$$\mathrm{Re} = \frac{\varrho \mathrm{V}\, \mathrm{D}_h}{\mu} \tag{1}$$

Equation (2) was used for calculation of average heat transfer coefficient (ha) proposed by Han and Zhang (1992), where Ts – test plate average surface temperature and Tb - bulk temperature of air.

$$\mathrm{ha} = \frac{\mathrm{Q_{net}}}{\mathrm{A(T_s - T_b)}} \tag{2}$$

The net heat supplied (Qnet) was computed from the total heat supplied minus heat loss from the test section, also found maximum heat loss below 13% from the test channel. The average Nusselt number was computed by equation (3) proposed by Luca Baggetta et al. (2017) where ha- average heat transfer coefficient, Dh - rectangular channel hydraulic diameter and k- thermal conductivity of air. Nusselt number results of plain plate are normalized with modified Dittus-Boelter/Sieder and Tate correlation (4).

$$\mathrm{Nu} = \frac{\mathrm{ha\, D}_h}{\mathrm{k}} \tag{3}$$

$$\frac{Nu}{Nu_o} = \frac{hD_h/k}{0.021Re^{0.8}Pr^{0.4}} \tag{4}$$

Frictional factor was calculated using Eq. (5) considering the pressure loss along the test channel and it is required to evaluate the thermal performance. Plain duct experimental friction factor result was normalized with Blasius correlation [24] and calculated using equation (6).

$$\mathrm{f} = \frac{(\mathrm{Pi - Pe})}{[(4(\mathrm{L/\,D_h})\,(1/2\,\rho V^2)]} \tag{5}$$

$$\frac{\mathrm{f}}{\mathrm{f_0}} = \frac{\mathrm{f}}{0.079\mathrm{Re}^{-1/4}} \tag{6}$$

Thermal performance (η) is computed by equation (7) proposed by Luca Baggetta et al. (2017) and for calculation considered the friction factor ratio and Nusselt number ratio.

$$\eta = \frac{(Nu/Nu_0)}{(f\,/\,f_{\,0})^{1/3}} \tag{7}$$

When determining the thermal performance in the experimental investigation of the multi semicircular rib - dimple hybrid channel, several key assumptions are typically considered. The system is assumed to be in a steady-state, meaning that the temperatures and heat fluxes are constant over time. This simplifies the analysis by eliminating the need to account for transient effects [24]. A uniform heat flux is applied to the channel walls. This assumption ensures that the heat input is consistent along the length of the channel, facilitating a more straightforward analysis of the heat transfer characteristics. The thermophysical properties of the working fluid, such as thermal conductivity, viscosity, and specific heat, are assumed to be constant. This assumption is valid if the temperature range within the channel is not large enough to cause significant variations in these properties. The contribution of thermal radiation to the overall heat transfer is assumed to be negligible compared to convection. This is a reasonable assumption for typical fluid flow conditions in heat exchangers and cooling channels where convective heat transfer dominates. The flow is assumed to be fully developed both hydrodynamically and thermally. This means that the velocity and temperature profiles have stabilized and do not change along the length of the channel, except at the entrance and exit regions.

Uncertainty Analysis

The experimental uncertainty was calculated using the method recommended by Kline and McClintock [25]. The maximum error found in pressure drop, flow rate and temperature measurement are ±3.4 %, ±3.1 % and ±0.7 0C respectively. The ambiguity in the Nusselt number was observed up to 9.5 % and the maximum experimental ambiguity observed up to 7.7 %. in the friction factor [26]. Uncertainty analysis is an essential aspect of experimental research, as it quantifies the degree of confidence in the measured data. This analysis allows researchers to understand the reliability and accuracy of their experimental results, accounting for possible errors or uncertainties in measurements.

Normalize Smooth Duct Results with Correlations

To validate the experimental data of plain duct, its results are verified with correlation results. The experimental results of Nusselt number was verified with the results of modified Dittus-Boelter and Sieder-Tate correlation [27] as shown in equation (8, 9). Experimental friction factor for smooth duct was obtained from the recorded data and normalized with the result obtained from modified Blasius correlation [28] as shown in equation (10).

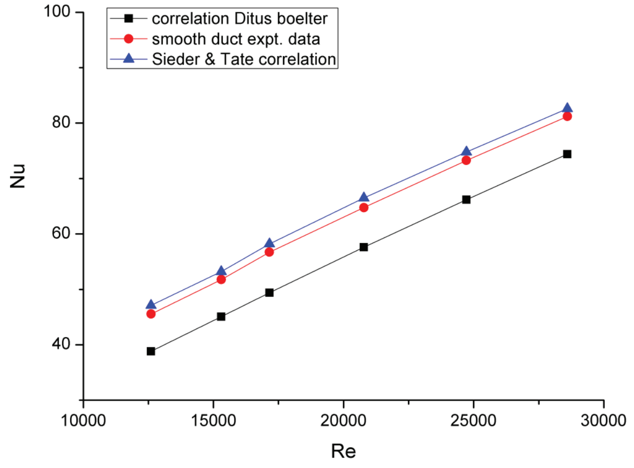


Figure 4. Deviation in the experimental and correlation value of plain duct.

$$\mathrm{Nu = 0.0230\ Re0.8\ Pr\ 0.33(\mu/\mu w)0.14} \qquad (8)$$

$$\mathrm{Nu = 0.023\ Re\ 0.8\ Pr\ 0.4} \qquad (9)$$

$$\mathrm{f = 0.079\ Re\ {-1/4}} \qquad (10)$$

Figure 4 presents the plot of correlation and experimental value of Nusselt number for plain duct against Reynolds number. From graph concluded that experimental results was nearer to the Sieder-Tate correlation than Dittus bolter correlation. The average error in the Nusselt number was found between ± 8.5 to 10.3%, also the friction factor error was found 6.2 to 8.5 % than Blasius correlations. Therefore it is presumed that experimental data are in good agreement with the correlation data indicated in the literature survey.

RESULTS AND DISCUSSIONS

Nusselt number and friction factor are calculated from collected experimental data and presented at a range of Reynolds number from 12000 to 30000. The result of friction factor and Nusselt number of multi semicircular rib and compound channels are compared with each other to determine the optimal rib-dimple configuration for cooling of gas turbine blade.

Heat Transfer in Ribbed Duct

This section discusses the rib alone and compound channel effect on the enhancement of heat transfer. Figure 5 presents the Nusselt number for rib and dimple alone channel. It indicates that multi semicircular rib performed better than plain and dimple duct, augmented average 96 and 68 % heat transfer than plain and dimple duct respectively. Rib improved heat transfer because ribs disturbed, promote flow missing and induced diverse secondary flows. In case of multi semicircular rib its two small curvature shape created two different more heat transfer area in front of ribs and two low heat transfer region behind the ribs, due to that observed heat transfer enhancement in multi semicircular rib [29].

Multi semicircular ribs improved the heat transfer but also increased pressure loss, to get additional enhancements generally increased number of ribs but other side pressure loss also improved by higher percentage. To achieve more enhancements in the heat transfer by virtue of minor rise in pressure loss, currently used combination of two methods such as rib -dimple, protrusion-dimple, rib- protrusion. but enhancement of dimple compound structure depends on number of dimples and depth of dimple.

In the existing study presented combination of rib-dimple structure, as dimple has less friction over other enhancement methods. In the current work two types of cases studied, in first case two dimples are followed by multi semicircular rib, means total 10 dimples and five ribs are replaced by ten ribs as shown in Figure (6 c). In second case four dimples followed by multi semicircular rib means total 20 dimples and five ribs tested. In this channel dimples position are such that two dimples kept horizontally and

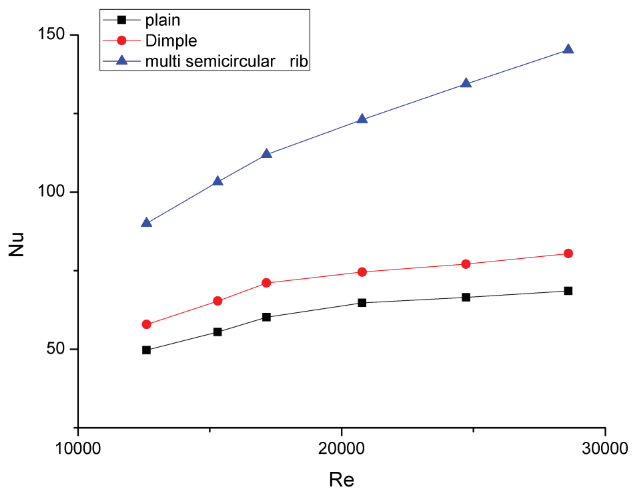


Figure 5. Variation of Nusselt number with Reynold's number (multi semicircular rib).

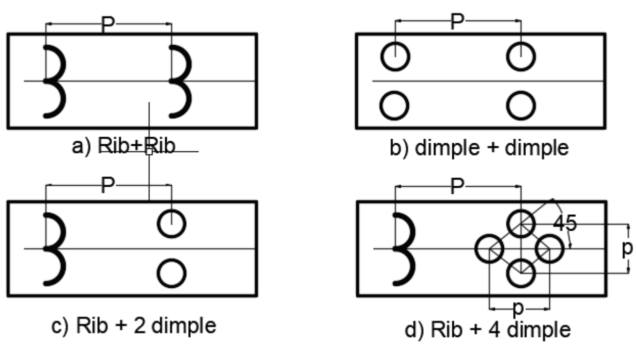


Figure 6. Rib, dimple alone and rib - dimple position.

vertically each, also pitch between dimples are same (horizontal and vertical) and made 45 deg. inclination angles with each other as presented in Figure (6 d).

Figure 7 shows result of Nusselt number for tested geometries, indicates that Nusselt number was maximum for compound duct with 20 dimples than rib alone and 10 dimples compound channel. It means that compound channel shows more enhancement in heat transfer related to the rib alone channel, on the other hand 10 dimples compound channel heat transfer observed less compared to the multi semicircular rib. Enhancement of heat transfer using dimples depends on many factors such as number of dimples, position diameter and depth of dimple of dimple. Compound channel with 20 dimples indicates more heat transfer and compound channel with 10 dimples shows less heat transfer compared to the rib channel. Compound channel with 20 dimples shows 25 and 30 % more heat transfer than multi semicircular rib and 10 dimples compound duct respectively. In case of 20 dimples compound duct position of dimples such that, behind and in front of every half curvature portion of rib trailed by one dimple each, also behind and in front of meet point of two curvature shape followed by one dimple each. Due to such position of dimples more mixing of primary and secondary vortices observed. In this compound structure the secondary flows creating from the ribs will undergo additional improvement due to the dimples and the joint effect of the flow separation layer of dimples and the secondary flows produced by the ribs will result in improvement of heat transfer. It is observed from the present wok and earlier work of Patil et al. (2021) that heat transfer was maximum in the compound channel compared to the rib alone channel.

In case of 10 dimples compound channel less enhancement found because of less number of dimples applied in channel also turbulence created by multi semicircular rib was not fully mixed with dimples. Enhancement of 10 dimples compound duct found somewhat less than rib channel but very less than 20 dimples compound channel. From this result dimples involvement in the enhancement are seen, as one rib replaced by two dimples result differed by small percentage than rib channel, but if increased the number of dimples and change position of dimple then found more augmentation in the heat transfer. To increase the number of dimples has limitation, as if only increased the number of dimples, pressure drop also increased so consider optimum number of dimples. Enhancement through dimples depends on depth, diameter, position and quantity of dimples.In the present compound channel work optimum values of thesse parameters are considered. Figure 8 shows the plausible flow structure for dimple surface having diameter 20 mm and depth ratio δ/D = 2.

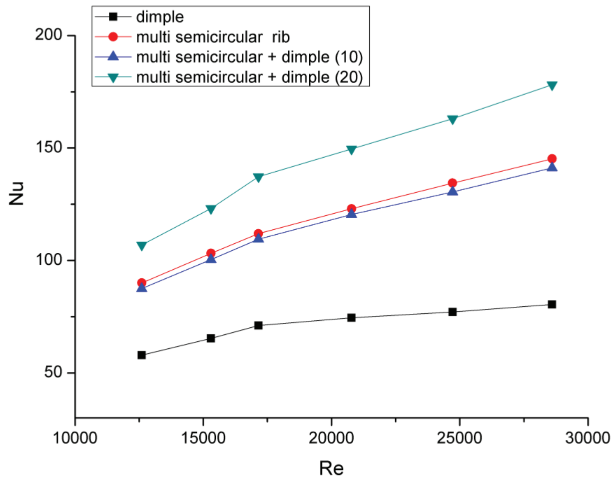


Figure 7. Nusselt number versus Reynolds number for different configurations.

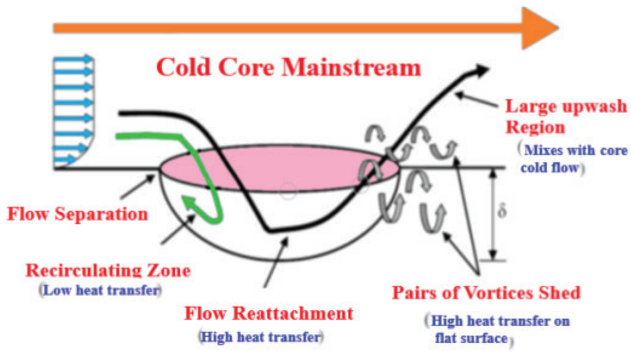


Figure 8. Plausible flow structure of dimple.

Friction Factor in Ribbed Duct

In this section, the friction factors for rib and compound channels are discussed, starting with the rib channel followed by the compound channel. The friction factors for the multi-semicircular rib and dimple channels are presented in Figure 9. It was found that the multi-semicircular rib channel exhibited, on average, 200% and 102% more friction compared to the plain and dimple ducts, respectively. This increase in friction is attributed to the ribs creating disturbances and retardation in the flow. The multi-semicircular ribs, with their two curvatures, offered an increased area to the flow, which resulted in higher turbulence and, indirectly, an increased pressure drop. In comparison, the dimple channel showed less friction than the rib channel.

Figure 10 shows the friction factor for rib, dimple, and compound channels, displaying a progressively reducing trend as the Reynolds number increases. This occurs due to the suppression of the viscous sublayer; as the Reynolds number increases, the boundary layer thickness decreases, resulting in improved fluid velocities within the boundary layer. The compound channel with 20 dimples exhibited a better friction factor than the multi-semicircular rib and the compound channel

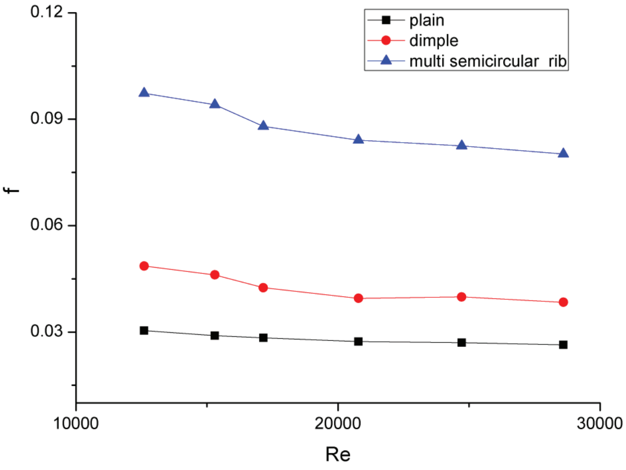


Figure 9. Friction factor variation with Reynolds number (ribs alone and dimple channel).

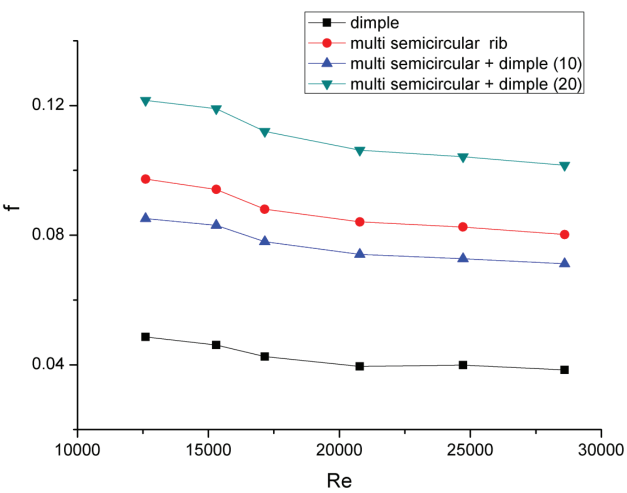


Figure 10. Variation of friction factor with Reynolds number (all tested configurations).

with 10 dimples. In the case of the compound duct with 10 dimples, five ribs are replaced by ten dimples. Since dimples create less friction than ribs, this configuration results in lower friction. Dimples enhance the flow area at the narrowest cross-section, leading to a decrease in flow velocity and a reduction in turbulent mixing in the mainstream flow area, which helps reduce the pressure drop. The compound channel with 20 dimples showed 19% more friction than the rib channel, while the compound channel with 10 dimples showed 11% less friction than the rib channel. Additionally, the compound channel with 20 dimples exhibited 36% more friction than the compound channel with 10 dimples. These findings were also observed by Yonghui Xie et al. (2017).

In case of 20 dimples compound channel four dimples applied after each rib if one or two dimples used friction found may be less but to get further enhancement applied more dimples, so combined effect of four dimples along with rib found more friction. Friction loss in dimples occurred due to depth of dimple, as depth increased friction also increased. The turbulent mixing in the downstream half of the dimple was significantly augmented because of flow attachment and impingement mainly at the rear rim of the dimple, which can consequently, increased the friction. In the present compound channel optimum parameters considered due to that found less growth in the friction over rib channel but other side heat transfer improved by more percentage. From this concluded that to achieve more percentage heat transfer enhancement, increase small percentage of friction, this principle applied in the current compound channel.

Validations of Experimental Results

Experimental results are validated through simulation software STAR-CCM [30]. The realizable k–ε turbulence model with hexahedral mesh was used and validated using standard data obtained from literature. Figure 11 presents velocity contours of multi semicircular rib, 10 dimples and 20 dimples compound channel. Also Figure 12 presents Nusselt number contours of multi semicircular rib with 4 dimples (20 dimples compound channel) and indicates that Nusselt was more near rib portion and dimple corner portion. Rib backside area shows less Nusselt number compared to the front side area due to frontal area effect.

Figure 13 shows the variation in experimental and numerical Nusselt number for compound channel and multi semicircular rib. Simulation results observed near about 8 % higher than experimental results, also 20 dimples compound channel shows highest Nusselt number, as same trend of results observed during experimental work. In case of semicircular rib simulation results are 7 to 8 % higher than experimental results, as difference between both results found less, so it is presumed that experimental results are validated, same trend of simulation results observed by Kaur and Singh (2020).

Figure 14 shows the result of experimental and numerical friction factor of 20 dimples compound channel and multi semicircular rib. Found numerical results 10-11 % less than experimental results, also 20 dimples compound channel shows highest friction than other channel, same results were observed during experimentation. Friction factor of multi semicircular rib found less against 20 dimples compound channel, also seen less variation among experimental and numerical results of friction factor for compound and rib channel. Variance between experimental and numerical results occurred because of heat loss and instrument error in actual experimentation, whereas in numerical analysis an ideal condition was assumed.

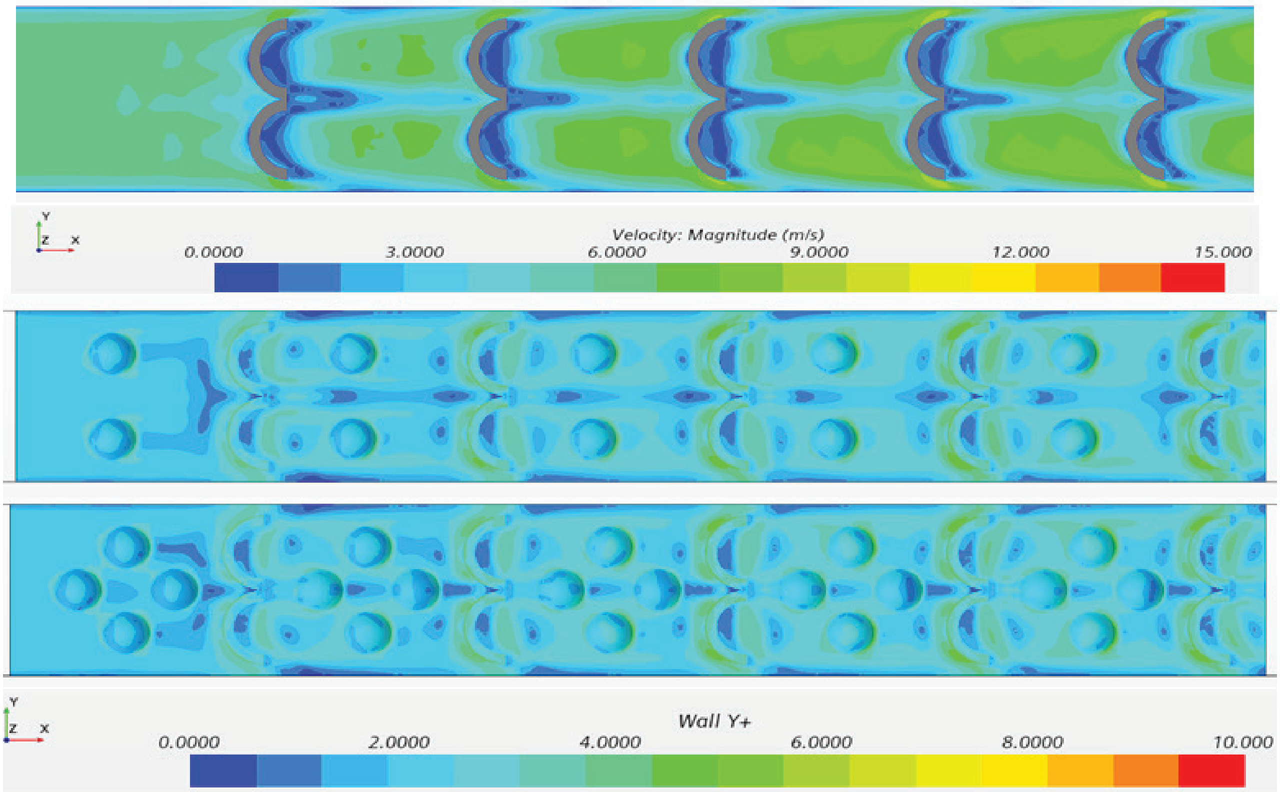


Figure 11. Velocity contours of multi semi rib and compound channel.

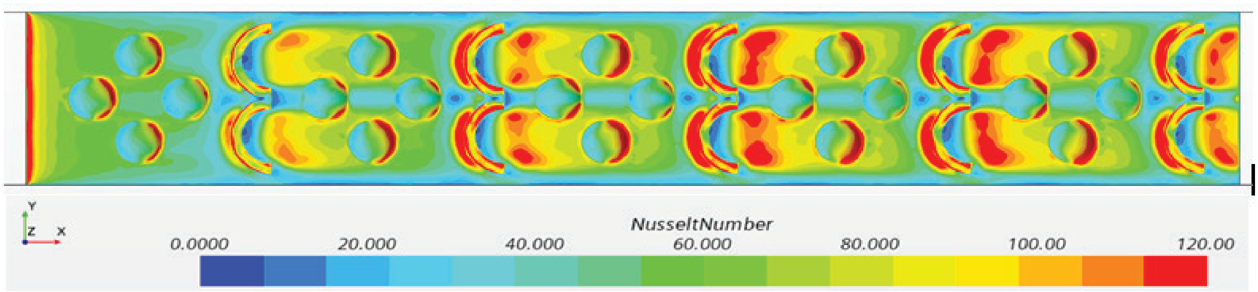


Figure 12. Nusselt number contours of multi semicircular rib with 20 dimples.

Optimization Technique

To select best configuration for thermal performance, applied multiple criteria decision-making (MCDM) techniques. In the engineering problem, to decide the optimum parameters from many variables; various methods are used such as: response surface method (RSM), TOPSIS, COPRAS, genetic algorithm. Among the MCDM techniques, TOPSIS method was a well-known optimization technique [31].

Technique for order Preference by Similarity to ideal Solution (TOPSIS) was one of the numerical methods among the multiple-criteria decision making techniques. It is suitable practical method with a simple mathematical model, also various benefits of TOPSIS methods such as rationality, simplicity, good computational efficiency, comprehensibility and capability to check the relative performance of each alternative in a simple mathematical form Total seven steps in TOPSIS method and the flow chart of the optimization process is shown in Figure 15.

Outcomes of TOPSIS method are shown in Table 2, indicates that 20 dimple compound channel performed best than 10 dimples compound channel, multi semicircular rib and dimple alone channel. From result table concluded that optimization results are near about same as experimental results, found less than 10% difference.

Experimental result of multi semicircular rib and compound channel are validated using CFD and TOPSIS method, found same trend of results, also seen less

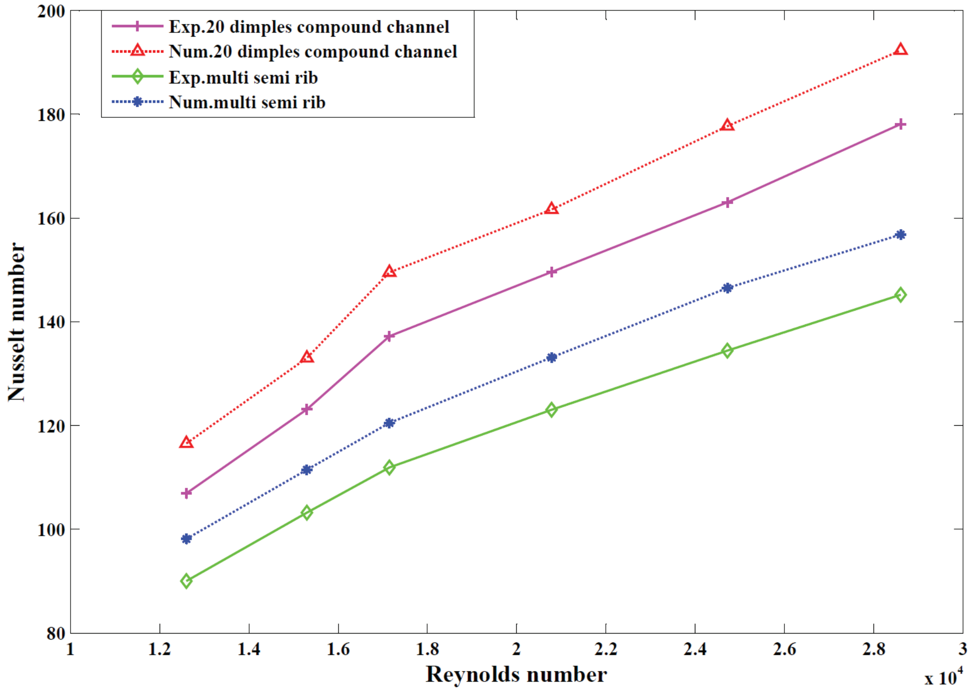


Figure 13. Variation in experimental and numerical result of Nusselt number.

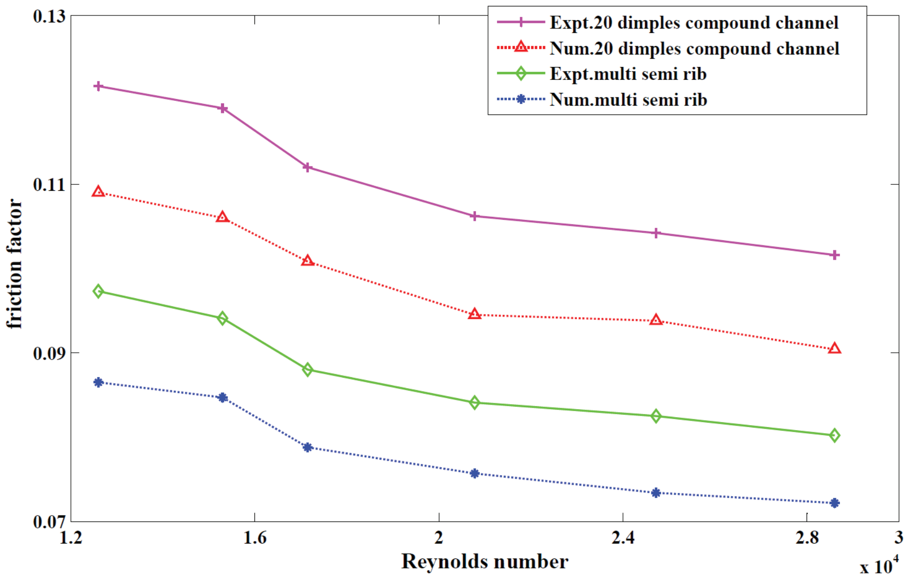


Figure 14. Variation in experimental and numerical result of friction factor.

difference between these results, so said that experimental results are validated [32].

Thermal Performance of Configurations

Thermal performance was determined by taking account the result of heat transfer and frictional losses. Figure 16 shows the thermal performance of tested structures, the compound channel with 20 dimples performed

Table 2. Outcomes of TOPSIS method

RANK		Ci
20 dimples compound channel	1	0.7431
10 dimples compound channel	2	0.5619
Multi semicircular Rib	3	0.4813
Dimple channel	4	0.3270

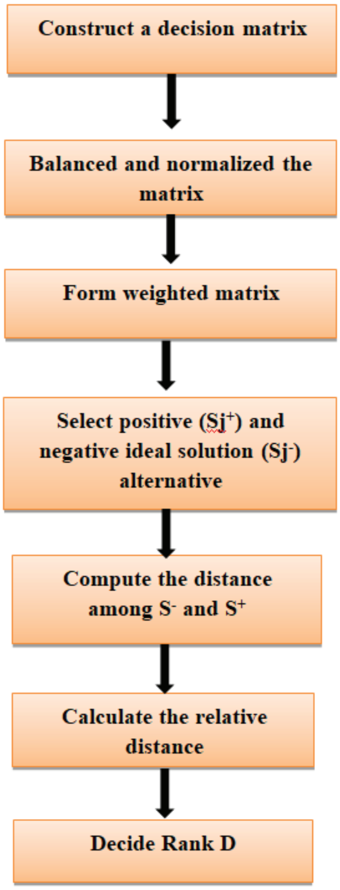


Figure 15. Optimization process flow chart (TOPSIS method).

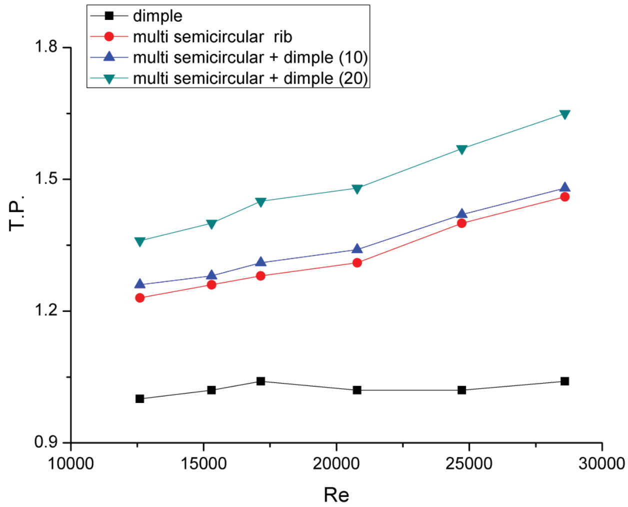


Figure 16. Thermal Hydraulic Performance of different configurations.

better than the multi semicircular rib and 10 dimples compound channel. It shows additional heat transfer enhancement than the frictional losses compared to the all tested configurations. The compound channel with 10 dimples have less heat transfer over multi semicircular rib but due to a small friction it performed better than the rib channel, likewise multi semicircular rib indicates lowest performance because of more friction.

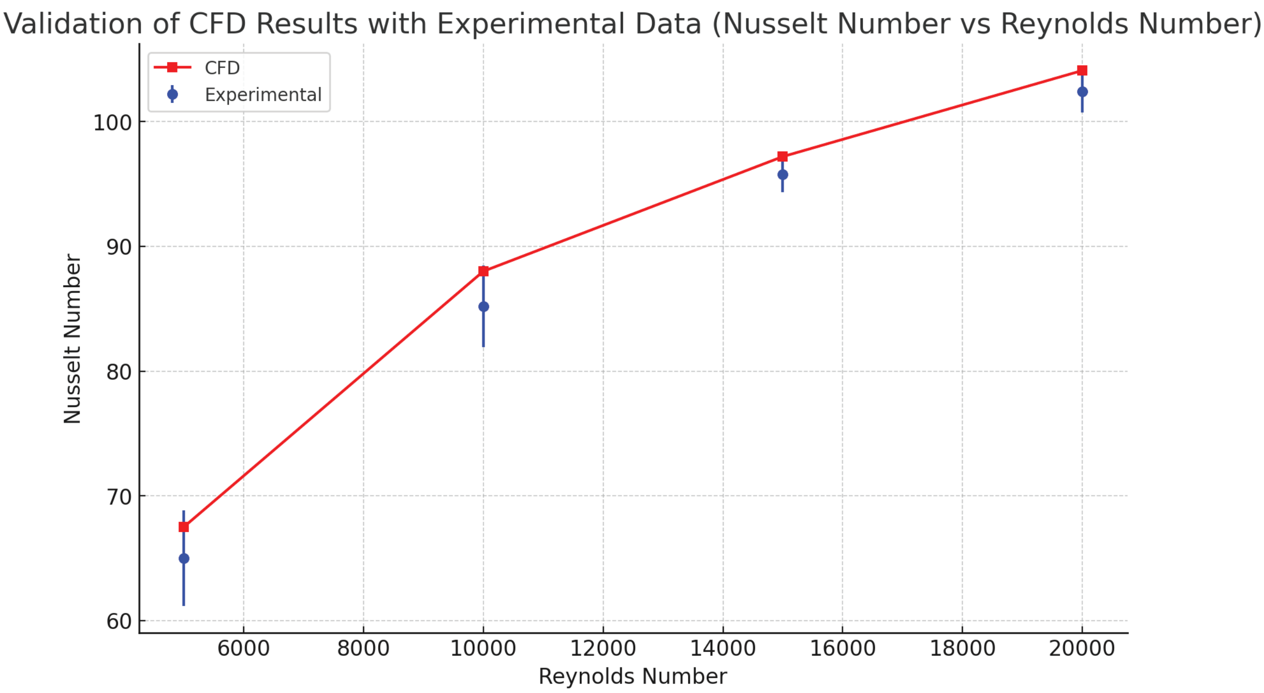


Figure 17. Error bars representing the percentage error between the CFD and experimental results.

The error bar plot comparing the experimental and CFD results for the Nusselt number as a function of Reynolds number. The plot includes error bars representing the percentage error between the CFD and experimental results as shown in Figure 17.

CONCLUSION

The study of heat transfer and flow friction characteristics in a rectangular channel with a multi semicircular rib and compound channel, using experimental methods, simulations, and optimization techniques, revealed that a compound channel with 20 dimples significantly enhanced heat transfer by 38% and 10% compared to plain and dimpled channels, respectively, but also increased friction by 29% and 16%. The 20-dimple compound channel outperformed the multi semicircular rib and 10-dimple compound channels, achieving up to 25% more heat transfer and 30% higher friction. While the multi semicircular rib offered slightly better heat transfer than the 10-dimple compound channel, the latter performed better overall due to lower friction. Additionally, increasing the number of dimples in the compound channel improved heat transfer but also increased friction.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

[1] Han JC, Zhang YM. High performance heat transfer ducts with parallel broken and V-shaped broken ribs. Int J Heat Mass Transf 1992;35:513−523. [CrossRef]

[2] Park J, Park S, Ligrani PM. Numerical predictions of detailed flow structural characteristics in a channel with angled rib turbulators. J Mech Sci Technol 2015;29:4981−4991. [CrossRef]

[3] Patil PS, Borse SL. Recent studies in internal cooling of gas turbine blade: a review. Int J Appl Eng Res 2018;13:7131−7141.

[4] Baggetta L, Satta F, Tanda G. A possible strategy for the performance enhancement of turbine blade internal cooling with inclined ribs. Heat Transf Eng 2019;40:184−192. [CrossRef]

[5] Abraham S, Vedula RP. Heat transfer and pressure drop measurements in a square cross-section converging channel with V and W rib turbulators. Exp Therm Fluid Sci 2016;70:208−219. [CrossRef]

[6] Promvonge P, Thianpong C. Thermal performance assessment of turbulent channel flows over different shaped ribs. Int Commun Heat Mass Transf 2008;35:1327−1333. [CrossRef]

[7] Seo JW, Afzal A, Kim KY. Efficient multi-objective optimization of a boot-shaped rib in a cooling channel. Int J Therm Sci 2016;106:122−133. [CrossRef]

[8] Kim KM, Lee H, Kim BS, Shin S, Lee DH, Cho HH. Optimal design of angled rib turbulators in a cooling channel. Heat Mass Transf 2009;45:1617−1625. [CrossRef]

[9] Rao Y, Feng Y, Li B, Weigand B. Experimental and numerical study of heat transfer and flow friction in channels with dimples of different shapes. J Heat Transf 2015;137:031901. [CrossRef]

[10] Kanargi OB, Lee PS, Yap C. A numerical and experimental investigation of heat transfer and fluid flow characteristics of a cross-connected alternating converging–diverging channel heat sink. Int J Heat Mass Transf 2017;106:449−464. [CrossRef]

[11] Nazari S, Zamani M, Moshizi SA. Comparative study on the influence of depth, number and arrangement of dimples on the flow and heat transfer characteristics at turbulent flow regimes. Heat Mass Transf 2018;54:2743−2760. [CrossRef]

[12] Gupta A, Kumar M, Patil AK. Enhanced heat transfer in plate fin heat sink with dimples and protrusions. Heat Mass Transf 2019;55:2247−2260. [CrossRef]

[13] Sahu MK, Pandey KM, Chatterjee S. Thermo-hydraulic performance of rectangular channel roughened with combined semi-circular and triangular ribs. Heat Mass Transf 2019;55:2889−2900. [CrossRef]

[14] Promvonge P, Skullong S. Heat transfer in solar receiver heat exchanger with combined punched-V-ribs and chamfer-V-grooves. Int J Heat Mass Transf 2019;143:118486. [CrossRef]

[15] Jing Q, Xie Y, Zhang D. Effects of channel outlet configuration and dimple/protrusion arrangement on the blade trailing edge cooling performance. Appl Sci 2019;9:2900. [CrossRef]

[16] Patil PS, Dhande KK, Borse SL. Experimental investigation of heat transfer and pressure drop using combination of ribs and dimples. Aust J Mech Eng 2023;21:628−640. [CrossRef]

[17] Xie Y, Shen Z, Zhang D, Ligrani P. Numerical analysis of flow structure and heat transfer characteristics in dimpled channels with secondary protrusions. J Heat Transf 2016;138:031901. [CrossRef]

[18] Xie Y, Shi D, Shen Z. Experimental and numerical investigation of heat transfer and friction performance for turbine blade tip cap with combined pin-fin-dimple/protrusion structure. Int J Heat Mass Transf 2017;104:1120−1134. [CrossRef]

[19] Rao Y, Zhang P. Experimental study of heat transfer and pressure loss in channels with miniature V rib-dimple hybrid structure. Heat Transf Eng 2020;41:1431−1441. [CrossRef]

[20] Kaur I, Singh P. Heat and flow characteristics of V-shaped protrusion/concavity combined with miniature V-ribs. Numer Heat Transf A Appl 2020;78:359−377. [CrossRef]

[21] Ferreira SB, Pilidis P. Comparison of externally fired and internal combustion gas turbines using biomass fuel. J Energy Resour Technol 2001;123:291−296. [CrossRef]

[22] MacIsaac B, Langton R, Belobaba P, Cooper J, Seabridge A. Gas turbine propulsion systems. Chichester: John Wiley & Sons; 2011. [CrossRef]

[23] Rajawat RS, Singh KK, Mishra VN. Approximation by modified Bernstein polynomials based on real parameters. Math Found Comput 2024;7:297−309. [CrossRef]

[24] Mishra VN, Rajawat RS, Sharma V. On generalized quantum Bernstein polynomials. In: Mishra RK, Patel MK, Kumar SD, editors. Advances in pure and applied algebra. Berlin: De Gruyter; 2023. p.149−160. [CrossRef]

[25] Kline SJ. The purposes of uncertainty analysis. 1985. Available at: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=d07dee57acdefe1fe87862cb7f9c74650c7c2f72 Accessed on Aug 26, 2025.

[26] Raiz M, Rajawat RS, Mishra VN. α-Schurer Durrmeyer operators and their approximation properties. Ann Univ Craiova Math Comput Sci Ser 2023;50:189−204. [CrossRef]

[27] McAdams WH, Drew TB, Bays GS Jr. Heat transfer to falling-water films. Trans ASME 1940;62:627−631. [CrossRef]

[28] Nakayama Y. Introduction to fluid mechanics. Oxford: Butterworth-Heinemann; 2018. [CrossRef]

[29] Pandey S, Rajawat RS, Mishra VN. Approximation properties of modified Jain-Gamma operators preserving linear function. Palestine J Math 2023;12:169−182.

[30] Zastawny M, Lardeau S. Application of Simcenter STAR-CCM+ for analysis of CFD sensitivities in NASA juncture flow simulation. In: AIAA aviation 2020 forum. Reston (VA): American Institute of Aeronautics and Astronautics; 2020. [CrossRef]

[31] Raiz M, Rajawat RS, Mishra LN, Mishra VN. Approximation on bivariate of Durrmeyer operators based on beta function. J Anal 2023;32:311−333. [CrossRef]

[32] Agrawal VK, Patil LN, Chavan KV, Nimbalkar UD. A computational analysis of heat transfer in solid and vented disc brakes: CFD simulation and thermal performance assessment. Multiscale Multidiscip Model Exp Des 2024;7:4735−4749. [CrossRef]