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# Heat transfer enhancement of turbulent nanofluid flow over various types of internally corrugated channels

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ABSTRACT

A numerical study is carried out to investigate the effects of different geometrical parameters and various nanofluids on the thermal performance of rib–grooved channels under uniform heat flux. The continuity, momentum and energy equations are solved by using the finite volume method (FVM). Three different rib–groove shapes are studied (rectangular, semi-circular and trapezoidal). Four different types of nanoparticles, $Al_2O_3$, CuO, $SiO_2$ and ZnO with different volume fractions in the range of 1% to 4% and different nanoparticle diameters in the range of 20 nm to 60 nm, are dispersed in the base fluids such as water, glycerin and ethylene glycol. The Reynolds number varies from 5000 to 25,000. To optimize the shape of rib–groove channels different rib–groove heights from $0.1D_h$ (4 mm) to $0.2D_h$ (8 mm) and rib–groove pitch from 5*e* (20 mm) to 7*e* (56 mm) are examined. Simulation results reveal that the semi-circular rib–groove with height of $0.2D_h$ (8 mm) and pitch equals to 6*e* (48 mm) has the highest Nusselt number. The nanofluid containing $SiO_2$ has the highest Nusselt number compared with other types. The Nusselt number rises as volume fraction increases, and it declines as the nanoparticle diameter increases. The glycerin–$SiO_2$ nanofluid has the best heat transfer compared to other base fluids. It is also observed that in the case of using nanofluid by changing parameters such as nanoparticle diameter, volume fraction and base fluids the skin friction factor has no significant changes.



## 1. Introduction

Forced convection heat transfer in a rib–groove channel has recently grabbed lots of researchers' attention. There are demands of improvement in convective heat transfer in engineering thermal systems in order to moderate size, weight and cost of heat exchangers. Numerous efforts have been made to enhance the heat transfer in the heat exchangers by using roughen surfaces or turbulators such as rib, groove and helical rib in disturbing the flow and in providing transverse/longitudinal vortices or three dimensional mixing. Several geometric shapes of the rib–groove channel including rectangular, triangular, square, and circular had been studied in the past decades considering various combinations of the imposed temperature gradients and cavity configurations. All these types of rib–groove channel were used in many engineering applications such as cross-flow heat exchanger, gas turbine airfoil cooling design, solar air heater blade cooling system, and gas cooled nuclear reactor [1]. Employing of nanofluids can be considered as a way to enhance the heat transfer in rib–groove channels. Nanofluids are fluids that contain suspended nanoparticles such as carbon based materials and metal oxides [2–4]. These nano-scale particles keep suspended in the base fluid. Thus, it does not cause an increase in pressure drop in the flow field. Past studies showed that not only nanofluids exhibit enhanced thermal properties, such as higher thermal conductivity and convective heat transfer coefficients, but also caused a lesser pressure drop in the flow field compared to the base fluid [5–9].

Investigations on heat transfer coefficient and pressure loss for different rib–groove channel configurations by both experimental and numerical works have been carried out by many researchers [10–24].

Karmare and Tikekar [10] presented an experimental investigation of heat transfer of the airflow in a rectangular duct. The top wall surface was made rough with metal ribs. It was found that the Nusselt number and friction factor can be enhanced up to 187% and 213%, respectively, by increasing the relative roughness height of grid ($e/D_h$) and relative length of grid ($l/s$). Tanda [11] investigated the effect of four different pitch-to-height ratios ($p/e$) including 6.66, 10.0, 13.33, and 20.0, on heat transfer in a rectangular channel with one-ribbed wall and two-ribbed wall. Results showed that $p/e = 13.33$ was slightly preferable for the 1RW case (especially at the highest Re values) while a smaller $p/e$ value ($p/e = 6.66$–10) gave the best performance for the 2RW case.

Chiang et al. [12] investigated the effect of length-to-gap ($L/B$) ratio on heat transfer enhancement in a ribbed rectangular channel. The spatially averaged Nusselt number over the rib roughened fin surface

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**Nomenclature**

| | |
|---|---|
| $C_p$ | specific heat at constant pressure, J kg$^{-1}$ K$^{-1}$ |
| $e$ | height of rib, mm |
| $f$ | friction factor $= \Delta P/(\rho u^2/2)(L/D)$ |
| $f_0$ | friction factor of plain channel |
| $H$ | height of the channel, mm |
| $h$ | heat transfer coefficient, Wm$^{-2}$ K$^{-1}$ |
| $k$ | thermal conductivity of fluid, Wm$^{-1}$ K$^{-1}$ |
| $L_0$ | length of the channel, mm |
| $L_1$ | fully developed region, mm |
| $L_2$ | length of the grooved channel, mm |
| $L_3$ | length of the smooth channel, mm |
| $N$ | Avogadro number |
| Nu | Nusselt number $= hD/k$ |
| $Nu_0$ | Nusselt number of plain channel |
| $P$ | pitch of rib–groove, mm |
| Pr | Prandtl number $= C_p\mu/k$ |
| $q$ | heat flux density, Wm$^{-2}$ |
| Re | Reynolds number $= \rho uD/\mu$ |
| $T$ | temperature, K |
| $u$ | flow velocity, ms$^{-1}$ |

*Greek symbols*

| | |
|---|---|
| $B$ | coefficient of thermal expansion, 1/K |
| $M$ | dynamic viscosity, kg/ms |
| $\nu$ | kinematic viscosity, m$^2$/s |
| $\Gamma$ | molecular diffusivity |
| $P$ | mass density, kg/m$^3$ |
| $\Phi$ | nanoparticle volume fraction |
| $\Delta$ | difference |

consistently increased with the decrease of $L/B$ ratio and the increase of Reynolds number. The effect of rib angle of attack ($\alpha$) and pitch-to-rib height ($p/e$) to achieve an optimal design was investigated by Kim et al. [13]. As a result of the optimization, the high regions of heat transfer and thermal performance induced by two design variables ($\alpha$ and $p/e$) appeared in ranges of $50 \le \alpha \le 60$. and $6.0 \le p/e \le 7.0$.

Bilen et al. [14] presented an experimental study on heat transfer and friction characteristics of a turbulent air flow in a tube with three different groove shapes. Among all grooved tubes, heat transfer enhancement was obtained up to 63% for circular groove, 58% for trapezoidal groove and 47% for rectangular groove, in comparison with the smooth tube. A computer code to study the heat transfer in a square duct with various rib shapes including square, triangular, trapezoidal with decreasing height in the flow direction, and trapezoidal with increasing height in the flow direction, was developed by Kamali and Binesh [15]. The results show that the trapezoidal ribs with decreasing height in the flow direction provide higher heat transfer enhancement and pressure drop than other shapes. Promvonge and Thianpong [16] performed experiments to estimate the heat transfer rate of air flow in a steady heat flux channel with different shapes of ribs including triangular, wedge and rectangular shapes. The results showed that triangular rib with staggered array showed better thermal performance than other ribs. Eiamsa-ard and Promvonge [17] carried out an experimental research to study the integrated effects of rib–grooved turbulators on the heat transfer properties in a rectangular duct with three types of rib–grooved orders including rectangular-rib and triangular groove (RR–TG), triangular-rib and rectangular groove (TR–RG) and triangular-rib with triangular groove (TR TG). Results show that ducts with RR–TG order create the highest heat transfer rate and friction factor than others. Liu and Gao [18] examined the heat transfer in two-dimensional channels with different ribs. The results showed that the resistance co-efficient and average Nusselt number in the channel with triangular ribs were the largest ones compared with others. Manca et al. [19] analyzed a ribbed channel with different geometric ratios and heights under constant heat flux with relative roughness pitch ($p/e$) ratio equal to 6, 8, and 10, for triangular, square, rectangular and trapezoidal ribs, respectively. The results showed that the Nusselt number increased as relative roughness height ($e/d$) increases and the best thermal performance was provided by triangular ribs with relative roughness width ($w/e$) = 2.0 and $p/e = 6$.

Peng et al. [20] showed that among different V-shaped ribs the 45° V-shaped continuous ribs have the best thermal/hydraulic performance. Promvonge et al. [21] conducted a numerical work to investigate heat transfer characteristics in a square-duct with inline 60° V-shaped ribs placed on two opposite heated walls. It was found that the maximum thermal performance was around 1.8 for the rib with BR = 0.0725 where the heat transfer rate was about 4.0 times above the smooth duct at lower Reynolds number.

Chandra et al. [22] reported an experimental study of surface heat transfer characteristics of a fully developed turbulent air flow in a square channel with transverse ribs on one, two, three, and four walls. The channel with two opposite ribbed walls showed a 6% increase in heat transfer over the one ribbed wall case. The three ribbed wall case showed a 5% increase over two ribbed wall case and the four ribbed wall case showed an increase of 7% over the three ribbed wall case. Wang et al. [23] done PIV measurement in a channel with regular rib on one wall. The highest Reynolds shear stresses happened at the leading edge of the rib. They did a quadrant analysis and found that ejection motions played a major role in the Reynolds shear stress in this region. Liu and Wang [24] presented a novel design of ribbed channel which was called semi-attached rib-design. The ribs were perforated at the rib corners to form two rectangular holes, so a portion of the fluid can pass through the holes. Five different structures of the rib (width ratios of the channel to hole) and two positions (transverse rib and 45° angled ribs) were analyzed. The numerical results show that the semi-attached ribs with 45° angle of attack can achieve a higher efficiency of synthetically heat transfer than that of the fully attached and detached rib channels.

A study on heat transfer distributions for straight and tapered two-pass channels with and without ribs for three Reynolds numbers was done by Ekkad et al. [25] Results showed that the tapered channel with ribs provided 1.5–2.0 times higher Nusselt number ratios over the tapered smooth channel in the first pass. In the after-turn region of the second pass, the ribbed and smooth channels provided similar Nusselt number ratios. Saha and Acharya [26] found that among ducts with various aspect ratios of 1:1, 4:1 and 1:4, heat transfer was maximum for the 4:1 AR case.

Zhu et al. [27] presented that the combination of rib roughness and winglets produced appreciable heat transfer enhancement. More than 450% enhancement of the Nusselt number was possible. Saha [28] found out that the transverse ribs in contact with wire–coil inserts perform better than when they were acting alone.

Lu and Jiang [29] did a study on the effect of various rib angles (i.e., 90°, 60°, 45°, 30°, 20°, 10° and 0°) on heat transfer of air in a rectangular channel. The results showed that the channel with 60° ribs had the best heat transfer performance, the channel with 0° ribs had the least pressure drop, and the channel with 20° ribs had the best thermal/hydraulic performance. Singh et al. [30] carried out an investigation on the effect of flow-attack-angle ($\alpha$) on thermo-hydraulic performance of rectangular ducts roughened with a new configuration of 'V-down rib having gap' on one wide wall. The results showed the best flow-attack-angle ($\alpha$) was from 30° to 75°. Smulsky et al. [31] conducted an experimental work on the effect of the angle of rib orientation relative to the flow of the coordinates varying from 50° to 90°. The local heat transfer maximum for the angle of 50° is approximately 40% higher, than for the angle of 90°.