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# Numerical study on characteristics of heat transfer and friction factor in a circular tube with central slant rods

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A B S T R A C T

In the present work, a numerical study on the characteristics of heat transfer and friction factor of laminar water flow in a circular tube fitted with a new tube insert (central slant rod inserts) is presented. Results reveal that the new inserts can fully disturb the core flow in the tube and create multiple longitudinal vortex structures, which are confirmed to be excellent flow structures for heat transfer enhancement. In addition, we carried out stereoscopic particle image velocimetry (SPIV) measurements in exactly the same facility as that of the numerical study to validate the accuracy of our numerical study. The results show good agreement between the experiment and numerical simulation. Following this, the effects of three parameters of central slant rods, including the slant angle, pitch and length in the radial direction, are discussed numerically. The computational results indicate that a moderate slant angle ranging from 20° to 30° can obtain the largest Nusselt number; however, the effect of slant angle on the friction factor is quite limited. The Nusselt number and friction factor both increase with a decrease in rod pitch and an increase in rod length in the radial direction. The simulation results show that the Nusselt number and friction factor are enhanced by 1.81–5.05 times and 2.49–6.92 times, respectively, to that of a plain tube. The performance ratio $R3$ values are in the range of 1.74–4.60. Empirical formulas for $Nu$ and $f$ are obtained based on calculation results. All results indicate that the central slant rod is a promising high-performance tube insert for heat transfer enhancement in practical applications.



## 1. Introduction

Heat exchangers are widely used in industrial fields such as power generation, chemical industry, aviation, aerospace, electronics, metallurgy, medicine, and materials. Considering the current energy crisis, it is significant to intensify the heat transfer process of heat exchangers in order to save energy. Numerous heat transfer augmentation techniques have been proposed by scientists and researchers around the world [1]. These techniques are generally divided into two categories: passive techniques (requiring no external power) and active techniques (requiring external power).

For the tube side heat transfer in shell-and-tube heat exchangers, passive techniques including surface coating, wave surfaces, rough and extended surfaces, convoluted (twisted) tube and tube inserts (turbulators and vortex generators) are more widely used because no external power is required. As a significant group of enhancement techniques, various tube inserts have been researched and proposed for heat transfer enhancement. Among them, the twisted tape technique has been widely used to produce compact heat exchangers due to its low cost and ease of manufacture and installation. Manglik and Bergles et al. [2,3] conducted experimental investigations of heat transfer and pressure drop in a tube fitted with inserts of twisted tape under laminar and turbulent flow conditions. Their results show that the twisted tape could induce turbulence and vortex motion (swirl flow) which led to a thinner boundary layer and consequently the generation of a higher heat transfer coefficient. On the other hand, the swirl flow induced by the twisted tape cause an increase in flow resistance which resulted in performance factor, at an equivalent pumping power, less than unity. In order to improve the thermal–hydraulic performance, various attempts have been made to modify the twisted tape technique. Some of them aimed to reduce the friction loss [4–7]: Saha et al. [4] presented the characteristics of friction and heat transfer for laminar flow in a circular tube fitted with regularly spaced twisted-tape elements; Jaisankar et al. [5] investigated the characteristics of friction and heat transfer for twist fitted with rod and spacer inserts in a tube; Krishna et al. [6] studied the heat transfer and pressure drop of a circular tube fitted with a straight full twisted tape. Results of these studies all indicate that the friction factor is observably reduced along with slight decrease in heat transfer compared to the corresponding value of traditional

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**Nomenclature**

| | |
|---|---|
| $l$ | the length of rod in the radial direction, mm |
| $p$ | the pitch of rod, mm |
| $q$ | heat transfer rate per unit area, W/m$^2$ |
| $D$ | inner diameter of the tube, mm |
| $L$ | the full length of tube, mm |
| $T$ | temperature of water, K |
| $T_c$ | temperature at the center position of inlet cross-section, K |
| $u$ | flow velocity, m/s |
| $u_c$ | velocity at the center position of inlet cross-section, m/s |
| $R$ | inner radius of the tube, mm |
| $r$ | the distance between the fluid particle and the center of the tube, mm |
| $c_p$ | specific heat at constant pressure of water, J/kg K |
| $Re$ | Reynolds number |
| $Nu$ | Nusselt number |
| $f$ | friction factor |
| $u_i$ | the velocity component in the three-dimensional space, m/s |
| $h$ | heat transfer coefficient, W/m$^2$ K |
| $P$ | pressure of water, Pa |
| $T_w$ | temperature on the tube wall, K |
| $T_m$ | fluid bulk temperature inside tube, K |
| $R3$ | comprehensive heat transfer performance coefficient |
| $Nu_0$ | Nusselt number of a plain tube |
| $f_0$ | friction factor of a plain tube |
| $S$ | non-dimensional slant angle |

*Greek symbols*

| | |
|---|---|
| $\theta$ | the slant angle of rod, ° |
| $\rho$ | density of water, kg/m$^3$ |
| $\mu$ | dynamic viscosity of water, kg/m s |
| $\lambda$ | thermal conductivity of water, W/m K |
| $\beta$ | synergy angle, ° |
| $\theta_1$ | synergy angle, ° |

twisted tape, and consequently the thermal–hydraulic performance is improved. Other researchers aimed to further enhance the heat transfer on the basis of typical twisted tapes [8–11]: Tarasevich et al. [8] proposed twisted tapes with wire-wound or wire-laced ribs on its surface to enhance the heat transfer; Eiamsa-Ard et al. [9] experimentally studied the performance assessment in a tube with alternate clockwise and counter-clockwise twisted-tape inserts; Murugesan et al. [10] and Chang et al. [11] investigated the inserts of V-cut twisted tape and broken twisted tape, respectively. They found that these modifications on twisted tape inserts can give assurance for the enhancement of both the heat transfer rate and the thermal enhancement factor.

In addition, various other forms of tube inserts have been proposed [12–19]. Martínez et al. [12] experimentally studied the heat transfer of laminar and transitional Newtonian and non-Newtonian flows in tubes with wire coil inserts. The results indicated that the wire coil inserts could enhance heat transfer when the Reynolds number is larger than 500, and the maximum Nusselt number augmentations of 7.5 at $Re = 1900$ is achievable. Fan et al. [13] numerically investigated turbulent heat transfer and flow characteristics in a circular tube fitted with louvered strip inserts. It was found that the louvered strip insert has a fairly good overall thermo-hydraulic performance with the *PEC* value lying in the range of 1.60–2.05. Jasiński [14] proposed a ball turbulent inserts fitted in a circular tube and numerically investigated the effects of diameter ratio and longitudinal distance ratio on the thermo-hydraulic performance of turbulent flow. The results show that the Nusselt number increases with an increase in diameter ratio, and the Nusselt number increases initially and then it begins to decrease with an increase in longitudinal distance ratio. Zhang et al. [15] studied numerical characteristics of the heat transfer and friction factor in a tube fitted with helical screw-tape without core-rod inserts. It was found that thees inserts could obtain a good overall heat transfer performance with an *PEC* value of between 1.58 and 2.35 when *Re* number ranges from 4000 to 20,000. Deshmukh et al. [16] developed a vortex generator in a circular tube and investigated its heat transfer characteristics and the friction factor for turbulent flow. It was found that this vortex generator could effectively strengthen the heat transfer with Nusselt numbers of approximately 150–500% higher than the corresponding values of a smooth tube. Zhang et al. [17] numerically studied heat transfer and flow characteristics of a tube fitted with a double spiral spring. They found that the double spiral spring inserts could obtain augmentation of 0.74–1.78 times for heat transfer and 2.83–8.79 times for friction factor when compared to a plain tube, and the *PEC* value could reach 1.5. Tu et al. [18,19] developed a small pipe insert which can guide the core flow through the small pipe to the boundary layer. It was found that the small pipe insert has an excellent overall thermo-hydraulic performance both in laminar and turbulent tube flow. The majority of these can produce swirl flow in the tube which causes better fluid mixing and consequently results in the enhancement of heat transfer.

Based on a survey of the literature, we find that most tube inserts are proposed from experience, and the designs lack theoretical guidance. In theory, tube flow can generally be divided into two parts: boundary flow and core flow [20]. Principles for increasing efficiency of core flow have been proposed by Liu and Yang [21,22]. They suggest that core flow temperature should be made more uniform by increasing the effective thermal conductivity of the fluid and enhancing the fluid mixing and disturbance of the core flow field. Others suggest that fluid shear force should be reduced by minimizing the velocity gradient of the flow, and the

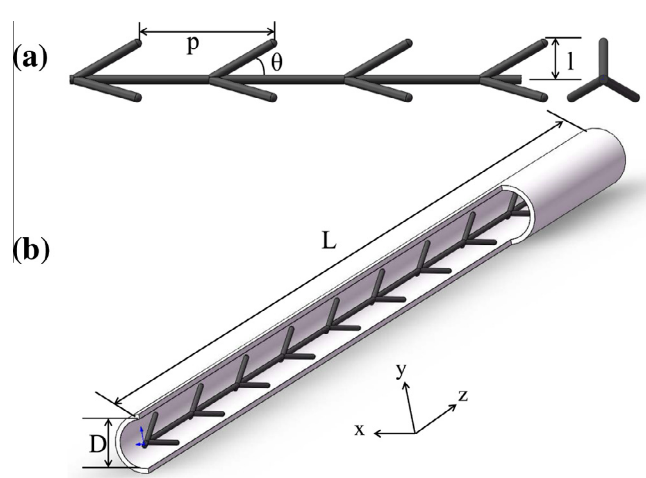


**Fig. 1.** (a) Geometry of the central slant rod insert, and (b) the circular tube fitted with central slant rod inserts.