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Heat transfer and friction characteristics of laminar flow through a circular tube with small pipe inserts

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ABSTRACT

A novel type of pipe insert was developed to improve convection heat transfer in the present work. Heat transfer performance and pressure drop was numerically studied. Pipe inserts with different dimensionless spacer length (S/D = 3.33, S/D = 5, S/D = 6.67, S/D = 8.33, S/D = 10, S/D = 11.67) were investigated at the Reynolds number range of 100–1750. Liquid water was used as the working fluid. The results showed that the maximal Nusselt number was enhanced by 3.4–10.3 times as that of the smooth tube. The friction factor resulted in an increase of 5.6–13.5 times. Performance Evaluation Criterion (PEC) values were approximately 1.91–4.33. The Nusselt number increased with the decrease in dimensionless spacer length. A small spacer length resulted in a high heat transfer coefficient. However, it also brought a high flow resistance and eventually deteriorated the heat transfer performance. Therefore, a suitable dimensionless spacer length S/D = 6.67 was recommended in this paper. The effect of pipe shape (R/D = 3.33, R/D = 5, R/D = 6.67) on the thermal characteristic was also investigated in this study. It indicated that the pipe shape had a little impact on the heat transfer performance in the laminar regime. Compared with other inserts, pipe inserts can transfer more heat for the same pumping power for their structure, because their special structure make it possible for the fluid to flow from the central region to the wall region, which reconstructs the velocity profile and temperature profile in the tube and results in a high heat transfer performance.

1. Introduction

Heat transfer enhancement has been widely applied to heat exchanger applications such as refrigeration, chemical industry, air conditioning, power generation etc. In the past century, an amazing number of enhancement techniques have been developed. Among theses techniques, displaced enhancement devices are simple and usually employed for single-phase flow both in the laminar and turbulent regime. Displaced enhancement devices are typically in the form of inserts such as twisted-tape, wire coil and helical screwed tape etc [1–4]. These inserted elements usually work as vortex generators, generating swirl flow and modifying velocity distributions. It brought the increase in heat transfer coefficient and critical heat flux, but at the expense of increased pressure drop. A high flow resistance sometimes could deteriorate the heat transfer performance. Therefore, it becomes a challenge to obtain a high heat transfer rate with a low increase in flow resistance. Over the past decades, researchers have designed varieties of inserts in their effort to get a high heat transfer performance with a reasonable increase in pressure drop.

Twisted-tape inserts have been widely used to improve heat transfer in both laminar and turbulent flow. Bas et al. [5]found that twisted tape placed separately from the tube wall instead of the attached type could also supply enhancement on heat transfer, especially at low Re number. It was useful in design of compact heat exchanger. Multiple short-length twisted tapes have drawn great attention of researchers, because it can yield a lower pressure drop for the same twist ratio compared with full-length twisted tapes. Ferroni et al. [6] found that multiple short-length twisted tapes yielded pressure drops at least 50% lower than those of most well known full-length tapes. Recently, modified tapes arouse considerable interest among the researchers. Murugesan et al. [7] and

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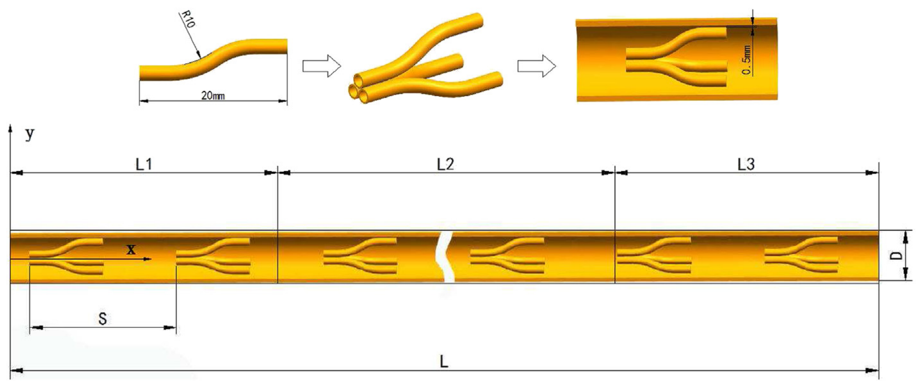

Fig. 1. The schematic of pipe inserts.

Bhuiya et al. [8] investigated V-cut twisted tapes, perforated twisted tape inserts, respectively. Numerous modified tapes were developed and reported in technique literatures such as broken twisted tape [9], serrated twisted tapes [10], delta-winglet twisted tape [11], conical cut-out turbulators [12]. Another method is used to improve heat transfer performance by changing the temperature profile instead of decreasing the thickness of the thermal boundary layer. Zhang et al. [13] presented a numerical study on triple and quadruple twisted tapes, where an increase of 171% and 182%, was obtained respectively. However, friction factors were 4.06–7.02 times, respectively, that of the plain tube. Huang et al. [14] found that the heat transfer rate of the tube with porous inserts is about 1.6–5.5 times larger than the smooth tube. Fan et al. [15] investigated heat transfer and flow characteristics numerically in a circular tube fitted with louvered strip inserts.

Much work has been done to enhance the heat transfer rate by reducing the thermal boundary layer. An increase in heat transfer rate usually brings an increase in the friction factor. The increase in the friction factor sometimes may deteriorate the heat transfer performance. Changing the temperature field seems to be a good way to solve this problem. However, it could be difficult to change the temperature field according to the temperature distribution. In this study, a novel type of pipe insert has been developed to improve the heat transfer rate by changing the velocity and temperature profiles in the tube. Their special structure makes it possible for the fluid to flow fluently from the central region to the wall region, and moreover, some unnecessary disturbance can be avoided. It is expected to obtain a high heat transfer rate with limited increase in flow resistance. The thermal performance of these pipe inserts was numerically investigated in the laminar regime.

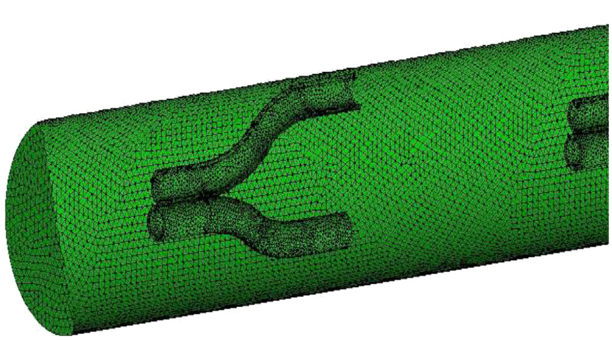

Fig. 2. 3D view for half of pipe inserts mesh.

2. Physical model

Fig. 1 shows the schematic of a circular tube with pipe inserts. Pipe inserts consist of three S-shape pipes. Each pipe is 2 mm in diameter, 0.5 mm in thickness and 20 mm in length. The insert shape is determined by a parameter of arc radii, R. They are placed in a circular tube with a regular spacer length, where 0.5 mm gap is between inserts and tube wall. The length and diameter of the tube are 500 mm and 12 mm, respectively. Investigation region length is L2 (300 mm), with an upstream length L1 (100 mm) and a downstream length L3 (100 mm). The effect of different space length (S = 40 mm, S = 60 mm, S = 80 mm, S = 100 mm, S = 120 mm, S = 140 mm) on heat transfer performance is investigated. The effect of pipe shape (R = 5 mm, 10 mm and 15 mm) on thermal characteristic is also studied in the present work. The spacer length (S) and arc radii (R) are changed to be dimensionless form (S/D, R/D). Water is used as the working fluid. The range of Reynolds number is between 100 and 1750.

3. Numerical analysis

3.1. Governing equations

Three dimensional stable incompressible flow and heat transfer model are used in this work. The investigation is carried out under following assumption which adopted by many researchers [16] [17]: the physical properties of fluid are constant; fluid is incompressible, isotropic and continuous; fluid is Newtonian fluid; the effect of gravity is negligible.

Equation of continuity, momentum and energy are given by:

Continuity equation

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0$$

Momentum equation

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right)$$

Energy equation

$$\frac{\partial \rho c_p u_j T}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\lambda\left(\frac{\partial T}{\partial x_j}\right)\right)$$

where ρ and p are fluid density and pressure; c_p and T are fluid specific heat and temperature; μ and λ are fluid viscosity and thermal conductivity, respectively.