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Boundary layer redevelops with mesh cylinder inserts for heat transfer enhancement

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ABSTRACT

In this paper, mesh cylinder inserts were adopted to enhance the convective heat transfer in a circular tube. The effect of open area rate ($P = 0.1$ mm, $P = 0.2$ mm, $P = 0.4$ mm), inlet closed type, spacer length ($S/D = 50/12$, $S/D = 75/12$, $S/D = 100/12$) and insert length ($L/D = 25/12$, $L/D = 50/12$, $L/D = 100/12$) on heat transfer performance were numerically investigated at the Reynolds number of 280–1800. The results show that mesh cylinder inserts has an excellent heat transfer performance in the laminar regime. It was mainly due to the high *Nu* number produced by boundary layer redevelopment at the inlet and the complex flow at the annular region also contributes to the high heat transfer rate. The excellent heat transfer performance is obtained at the cost of high flow resistance. To avoid sharply increase in the flow resistance, a small hole is cut in the closed inlet of mesh cylinder inserts, which can greatly decrease the friction factor without sharply decrease the heat transfer rate. The open area rate has little impact on the heat transfer rate and the best heat transfer performance is resulted from inserts with $P = 0.2$ mm. Heat transfer performance of mesh cylinder inserts is also affected by the spacer length, insert length. A relatively long spacer length ($S/D = 100/12$) and a short insert length ($L/D = 25/12$) are recommended in the design of heat exchanger in this work.

1. Introduction

Attempts to improve heat transfer performance have been recorded in the techniques literature for over 100 years [1]. The relevant technique involved increasing the heat transfer rate is normally referred to as enhancement, augmentation, or intensification. With the development of many years, a great number of enhancement techniques have been developed such as vortex generator, extended surface, porous media [2–4]. Among the enhancement, inserts have been widely accepted to increase the heat transfer rate in the circular tube for its advantage of simple structure, low cost and easy installment [5,6]. These inserts elements usually generate the swirl flow and the second flow, which can greatly increase the velocity gradient near the tube wall and the mixing intensity between the fluid [7]. Therefore a high heat transfer rate will be obtained, coupling with a high friction factor as well. Realizing the different effect between boundary layer and core flow on the heat transfer performance, the researchers made a great change in the geometry of inserts and have developed a variety of inserts such as serrated twisted tape [8], V-cut twisted tape [9], helical screw-tape [10], louvered strip inserts [11]. Some of them are so different from those traditional twisted tapes that even it is very difficult to name them. In spite of this, the greatest challenge is still to increase the heat transfer rate without sharply increasing the flow resistance.

Too much early work has been put on the effect of twisted-tapes on the heat transfer performance. Twisted-tapes usually produce the swirl flow and the secondary flow and it is inevitable to bring about a high friction factor. Compared with full-length twisted tapes, multiple short-length twisted tapes can yield a lower pressure drop for the same twist ratio. Saha et al. [12] reported that regularly-spaced twisted tape performed significantly better than full-length twisted tapes at high Reynolds numbers and that the pressure drop decreased by 40%. Ferroni et al. [13] found that multiple short-length twisted tapes yielded pressure drops at least 50% lower than those of most well known full-length tapes. The placement of twisted tapes also has an impact on the heat transfer performance. Bas and Ozceyhan [14] experimentally investigated the effect of twist ratio and clearance ratio on the heat transfer performance of a twisted tape inserted placed separated from the tube wall. The results showed that

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Nomenclature

A	surface area of test tube, m^2	T	temperature, K
c_p	specific heat of water, J/kg K	u	fluid velocity, m/s
d	insert diameter, m	v	mean velocity in the tube, m/s
D	tube diameter, m	λ	thermal conductivity, W/m K
f	friction factor	ρ	fluid density, kg/m^3
h	convective heat transfer coefficient, W/m^2 K	μ	fluid dynamic viscosity N s/m^2
L	length of insert		
l	length of test tube	*Subscripts*	
Nu	Nusselt number	i	X-direction
p	fluid pressure, N/m^2	j	Y-direction
Δp	pressure difference, N/m^2	f	fluid
q	heat flux density, W/m^2	w	wall
S	spacer length		

using twisted tape separately from the tube wall instead of attached type can also supply excellent heat transfer enhancement. In addition, it provides less contamination compared with the attached one. Mwesigye et al. [15] used wall-detached twisted tape inserts to enhance heat transfer in a parabolic trough receiver. The results showed that the heat transfer rate was increased about 169% and thermal efficiency was up to 10% over a receiver with a plain absorber tube. Recently, multiple inserts arouse the researcher's great interest. Vashistha et al. [16] carried out an experimental testing on the performance of multiple inserts. The results showed that the heat transfer and friction factor were 2.42 and 6.96 times that of smooth tube and the thermo-hydraulic performance factor was 1.26, resulted from a set of four counter-swirl twisted tapes with the twist ratio of 2.5. Abdolbaqi et al. [17] developed a twin twisted tapes to increase the heat transfer rate. They found that the twin counter twisted tapes (CTT) is more efficient than the twin Co-twisted tapes (CoTT). The flat tube with CTT can achieve an increase of approximately 22.5% and 61% to those with the CoTT and plain flat tube, respectively. Eiamsa-ard and Promvonge [18] also obtained the similar results. These inserts show an excellent heat transfer performance when compared with other traditional inserts. Apart from the two inserts mentioned above, many other modified tapes and the likes were developed such as V-cut twisted tape [19], pipe inserts [20], louvered strip inserts [21], wire coil inserts [22]. In addition, many previous works adopted porous medium to enhance the heat transfer rate. Porous material with a smaller porosity and higher thermal conductivity can further improve the heat exchanger performance [23]. SOzen and Kuzay [24] pointed out that the enhancement in heat transfer achieved by porous inserts will be at the cost of a large pressure drop. A pressure drop of large magnitude may limit its application. Pavel and Mohamad [25] found that the porous material can achieve a high heat transfer rate with a reasonable pressure drop increasing. The effective thermal conductivity of porous material should be carefully evaluated for an accurate simulation.

Recently, a new type of inserts, mesh cylinder insert, is developed to enhance condensation [26] by changing the flow pattern. This insert is made of thin stainless wire mesh, which has the shape of a cylinder and its inlet is closed by the same porous material. Mesh cylinder insert can achieve a high heat transfer rate of condensation. The researchers also find that the mesh cylinder insert has an excellent performance in convective heat transfer as well [27]. The open area rate of mesh cylinder inserts has a greatly impact on the heat transfer performance. An optimal value of open area rate is recommended in the recent work [28]. Compared with full length mesh cylinder insert, short mesh cylinder inserts (SMCI) can achieve a higher heat transfer rate. However, the high heat transfer rate is obtained at the cost of a high flow resistance. In order to avoid greatly increasing in the flow resistance, a small hole is cut in the closed inlet of mesh cylinder inserts in this paper. It is expected to cause the boundary layer redevelopment, increase the velocity gradient near the tube wall and enhance the mixing intensity between the fluids. A numerical method will be employed to investigate the thermal characteristic of this porous media inserts. The effect of inlet closed type, open area rate, insert length and spacer length on the heat transfer performance will be carefully analyzed.

2. Physical model

The testing mesh cylinder is shown in Fig. 1. This insert (0.1 mm thick, 10 mm diameter) was made of stainless wire mesh and its inlet is closed by the same porous media. The schematic diagram of a circular tube with mesh cylinder insets is shown in Fig. 2, where 1 mm gap is between inserts and tube wall, $d = 10$ mm, $D = 12$ mm, $l = 100$ mm, $L = 800$ mm, and S is the spacer length. In addition, a small hole is made in the closed inlet of the mesh cylinder, of which size is 6 mm. Investigation region length is 600 mm, with an upstream length of 100 mm and a downstream length of *100mm*. The effect of different spacer length ($S/D = 50/12$, $S/D = 75/12$, $S/D = 100/12$) and different insert length ($L/D = 25/12$, $L/D = 50/12$, $L/D = 100/12$) on heat transfer performance is investigated. Open area rate of $P = 0.1$ mm, 0.2 mm and 0.4 mm will also be investigated, where the P is pore size and their open area rates are 0.33, 0.5, 0.67 accordingly. Water is used as the working fluid. The testing range of the Reynolds number is between 280 and 1800.

3. Numerical method

The physical model was simplified as a two-dimensional model shown in Fig. 3. The computational domain is meshed with rectangular cells. The boundary layers and mesh cylinder wall region is refined with local grid refinement. Mesh independence is checked by using different grid system. Boundary conditions are: the tube wall is imposed a constant temperature condition; at the tube inlet, the fully developed velocity and temperature boundary condition is used. The fully developed velocity and temperature boundary condition is obtained by computing a long smooth tube which has the same physical dimension as the enhancement tube; at the outlet, the outflow boundary condition is applied. The numerical simulation was carried out by using commercial CFD software FLUENT 6.2.16.