ARTICLE IN PRESS

Theoretical & Applied Mechanics Letters ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Theoretical & Applied Mechanics Letters

journal homepage: www.elsevier.com/locate/taml

Letter

Heat transfer in turbulent tube flow inserted with loose-fit multi-channel twisted tapes as swirl generators

Suttisak Kunlabud [a], Varesa Chuwattanakul [b], Vichan Kongkaitpaiboon [a], Pitak Promthaisong [a], Smith Eiamsa-ard [a,*]

[a] *Faculty of Engineering, Mahanakorn University of Technology, Bangkok, Thailand*
[b] *Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand*

ARTICLE INFO

Article history:
Received 25 August 2017
Accepted 5 September 2017
Available online xxxx
*This article belongs to the Fluid Mechanics

Keywords:
Heat transfer
Heat transfer enhancement
Loose-fit multiple channel twisted tape
Swirling flow

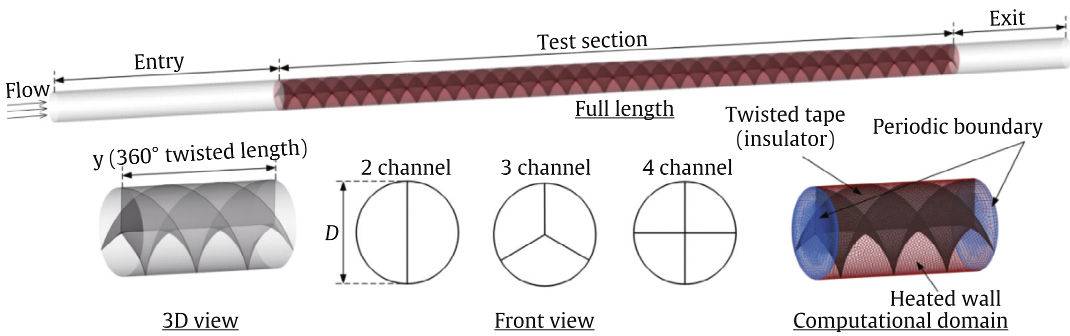
ABSTRACT

Heat transfer and flow behaviors in three-dimensional circular tubes with loose-fit multiple channel twisted tapes were numerically studied. The investigation was examined for Reynolds numbers (*Re*) ranging from 5000 to 15,000, by using air as testing fluid. Effects of the multiple channel number ($N = 2$, 3, and 4), clearance ratio ($CR = 0.0$, 0.025, 0.05, and 0.075) on heat transfer enhancement and flow friction were examined. The numerical results indicate that the tubes with loose-fit multiple channel twisted tapes perform higher heat transfer rates than the plain tube. The enhanced heat transfer rate is escorted with larger pressure drop. Both heat transfer and pressure drop increase with increasing multiple channel number (N) and decreasing clearance ratio (CR). Heat transfer augmented by the loose-fit multiple channel twisted tape with $N = 4$ is higher than those enhanced by the ones with $N = 2$ and 3 by around 9.5–17.8% and 5.8–7.8%, respectively. In addition, the loose-fit multiple channel twisted tapes with clearance ratio of 0.025, 0.05, and 0.075 give lower heat transfer rates than the one with $CR = 0.0$ by around 8.4%, 17.5%, and 28.8%, respectively.

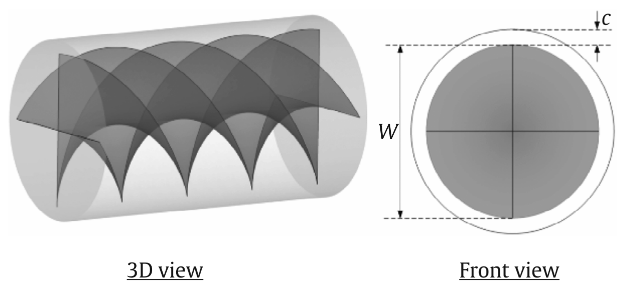
Heat exchangers have a wide range of applications from industrial fields to engineering devices such as power plant, air conditioning, refrigeration, food process and chemical industry, *etc* [1–4]. Different methods, techniques and theories have been investigated for heat transfer enhancement in heat exchangers. The major challenge in designing the enhancing devices is to improve heat transfer rate with enlarging pumping power. Several heat transfer augmentation methods (HTE) have been introduced and utilized, such as insert devices, extended surface, fluid vibration/rotation, and additional fluid, *etc* [5–12]. Among the techniques, inserting twisted tapes is one of the most popular techniques. Twisted tapes can be applied in all kinds of heat exchangers (solar air heater and solar water heater, and shell and tube heat exchanger, *etc.*) [13–20]. Hong et al. [21] studied the thermal and pressure drop behaviors in spiral grooved tubes inserted with dual overlapped tapes at different overlapped twisted ratios. Their result found that the heat transfer and friction factor increased with the decrease in the ratio of overlapped twisted. The spiral grooved tubes inserted with twin overlapped twisted tapes gave better heat transfer rates over than that the plain tube up to 177%, 168%, 153%, and 140%, for overlapped twisted ratio of 1.06, 1.56, 2.44, and 3.22, respectively. Abdolbaqi et al. [22] studied the influence of twin counter/co twisted tapes on thermohydraulic performance characteristics. Effect of twist ratio was also examined. They found that, thermohydraulic performance increased with decreasing twist ratio. At a given twist ratio thermal enhancement indices given by the counter-tapes were better than the ones performed by the co-tapes. Saravanan et al. [23] examined the heat transfer rate, frictional loss and thermohydraulic performance of solar water heater equipped with modified helix twisted. They reported that heat transfer and pressure drop given by the modified helix tape square/V-cut were lower than the typical tape. Singh et al. [24] conducted the heat transfer augmentation and fluid flow of roughened tubes fitted with solid ring tubular at various twist ratios. As compared to the plain tube, the heat transfer rate, friction factor and thermohydraulic performance of the roughened tubes fitted with solid ring tubular at twist ratios were up to 293%, 0.99 times and 1.61 time, respectively. Changcharoen et al. [25] compared the effect of co/counter (CoT/CT) dual-twisted tapes with that of the typical one on heat transfer enhancement behaviors. It was visible that the dual tapes offered better heat transfer rate than the typical tape at the entry section ($x = 0$ to $10D$). However, the opposite

* Corresponding author.
E-mail address: smith@mut.ac.th (S. Eiamsa-ard).

https://doi.org/10.1016/j.taml.2017.11.011



(a) Tube inserted with multi-channel twisted tape and grid generation.



(b) Tube inserted with loose-fit multi-channel twisted tape.

Fig. 1. Geometries of problem consideration.

results were found for $x > 10D$. Zheng et al. [26] investigated the heat transfer enhancement in a round tube equipped with dimpled twisted tape by using Al_2O_3/water nanofluid as the testing fluid. Influences of the dimple side and protrusion side on heat transfer and pressure loss behaviors were compared. They reported that the dimple side showed better performance in heat transfer augmentation than the protrusion one. Saysroy and Eiamsa-ard [27] investigated the thermohydraulic performance in a round tube with square cut twisted-tape inserts at various perforated width ratios and perforated length ratios. They observed that the heat transfer and pressure loss increase with decreasing perforated-width and perforated-length ratios while thermohydraulic performance increases as perforated width ratio increases. The maximum thermohydraulic performance of 1.37 was found at the largest perforated width ratio of 0.9 and the smallest perforated-length ratio of 0.7.

In order to extend the investigation in the field of heat transfer augmentation by swirl flow devices, the present work proposes the modified tapes in the form of loose-fit multiple channel twisted tape inserts. It is expected that the loose-fit multiple channel twisted tape insert will improve the core fluid disturbance and fluid mixing in tube. Effects of the number of multiple channel ($N = 2$, 3, and 4) and clearance ratio ($CR = 0.0$, 0.025, 0.05, and 0.075) on thermohydraulic performance are examined in turbulent regime using air as the working fluid. The flow structures of turbulent tube flow through loose-fit multiple channel twisted tape insert are described.

The computational domain for the flow in tubes inserted with loose-fit multi-channel twisted tapes is resolved by regular Cartesian elements, as demonstrated in Fig. 1. The pattern shown is limited for only 360° twist length due to the periodic flow. The parameters investigated were number of channel (N). The loose-fit multi-channel tapes were prepared at constant twist ratio of 3.0, three different numbers of channels (N) of 2, 3, and 4 and clearance ratios ($CR = c/D$) of 0.0 or tight-fit, 0.025, 0.05, and 0.075, respectively, as details seen in Fig. 1. The multi-channel twisted tapes were inserted along the tube. It is noteworthy that the plain tube (without multi-channel twisted tapes) was also tested for comparison. The inner tube surface and entry temperature were kept constant at 310 and 300 K while the outer tube surface was maintained under adiabatic condition.

The mathematical modeling involves the simulation of fluid flow and heat transfer enhancement characteristics in tube inserted with loose-fit multi-channel twisted tape. The continuity, momentum and energy equations can be written in the following forms:

Continuity equation :

$$\frac{\partial}{\partial x_i}(\rho\, u_i) = 0. \tag{1}$$

Momentum equation :

$$\frac{\partial}{\partial x_j}(\rho\, u_i u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\overline{u_i^{'} u_j^{'}}\right]. \tag{2}$$

Energy equation :

$$\frac{\partial}{\partial x_j}(\rho\, u_i T) = \frac{\partial}{\partial x_j}\left[(\Gamma + \Gamma_t)\frac{\partial T}{\partial x_j}\right], \tag{3}$$

where

$$\Gamma = \frac{\mu}{Pr} \quad \text{and} \quad \Gamma_t = \frac{\mu_t}{Pr_t}. \tag{4}$$

The Boussinesq hypothesis relates the Reynolds stresses to the mean velocity gradients as shown in the equation below:

$$-\rho\overline{u_i^{'} u_j^{'}} = \mu_t\left(\frac{\partial u_i}{\partial u_j} + \frac{\partial u_j}{\partial u_i}\right) - \frac{2}{3}\left(\rho k + \mu_t \frac{\partial u_i}{\partial x_i}\right)\delta_{ij}. \tag{5}$$

The steady state transport equations are written as:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon + S_k, \tag{6}$$