Chinese Journal of Chemical Engineering 23 (2015) 342–349

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

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

Fluid Dynamics and Transport Phenomena

3D numerical study on flow structure and heat transfer in a circular tube with V-baffles☆

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ARTICLE INFO

Article history:
Received 4 June 2013
Received in revised form 30 September 2013
Accepted 19 January 2014
Available online 10 November 2014

Keywords:
Periodic flow
Tube
Laminar flow
Heat transfer
Pressure loss
V-baffle

ABSTRACT

A 3D numerical investigation has been carried out to examine periodic laminar flow and heat transfer characteristics in a circular tube with 45° V-baffles with isothermal wall. The computations are based on the finite volume method (FVM), and the SIMPLE algorithm has been implemented. The fluid flow and heat transfer characteristics are presented for Reynolds numbers ranging from 100 to 2000. To generate main longitudinal vortex flows through the tested section, V-baffles with an attack angle of 45° are mounted in tandem and in-line arrangement on the opposite positions of the circular tube. Effects of tube blockage ratio, flow direction on heat transfer and pressure drop in the tube are studied. It is apparent that a pair of longitudinal twisted vortices (P-vortex) created by a V-baffle can induce impingement on a wall of the inter-baffle cavity and lead a drastic increase in heat transfer rate at tube wall. In addition, the larger blockage ratio results in the higher Nusselt number and friction factor values. The computational results show that the optimum thermal enhancement factor is around 3.20 at baffle height of $B = 0.20$ and $B = 0.25$ times of the tube diameter for the V-upstream and V-downstream, respectively.

1. Introduction

Turbulator is a technique for heat transfer augmentation and widely used in the industrial heat exchanger. Heat transfer system in chemical and biochemical industries is often installed with various types of turbulator to increase the efficiency of cooling or heating. The application of turbulators changes drastically the flow field and thus the distribution of the local heat transfer coefficient, leading to higher heat transfer rate. Although heat transfer is increased through the turbulator arrangement, the pressure drop of flow in the tube is also increased due to the turbulator effect. Therefore, turbulator spacing, angle of attack, configuration and height are among the most significant parameters in the design of tube heat exchangers.

Many types of turbulator have been studied, and many baffles or ribs have especially been used in many thermal systems. Flat or curved plated baffle is extensively employed in various applications for stabilizing and directing flow, controlling sloshing or waves, preventing overflow and mixing enhancement purposes [1,2]. An academic study on this topic was firstly reported by Berner *et al.* [3] who reported the effect of baffle presence in a shell and tube heat exchanger model using an approximate two-dimensional model. The turbulent flow and heat transfer between a periodical series of conducting parallel plates with surface-mounted heat sources were reported by Kim and Anand [4]. They found that the presence of the plates (as baffles in electronic cooling channels) would affect directly the friction factor and the Nusselt number and lead to an increase in heat transfer rate. Dutta and Dutta [5] carried out both experimental and numerical studies. Their results show effects of inclined baffles on friction loss and heat transfer of turbulent flow in a rectangular channel with constant heat flux on the upper wall. The baffle size, orientation and perforation on the average and local Nusselt numbers were also reported. They found that the size, positioning and orientation of the baffle have significant influence on internal cooling heat transfer. In addition, an optimum perforation density for perforated baffles leads to strong jet impingement phenomenon and maximizes heat transfer. Chen *et al.* [6] developed a mathematical model for three-dimensional numerical investigation of flow and heat transfer characteristics in cylindrical crystal growth systems. They reported that a baffle placed between the lower and upper chambers may reduce the flow strength but causes more uniform velocity and temperature distributions in the crystal growth zone (*i.e.* upper chamber). Moreover, they emphasized that location; thickness, shape and porosity of the baffle can influence effectively the growth process and should be studied in detail. Li and Braun [7] compared flow configuration and transport mechanisms in rectangular and cylindrical enclosures with and without baffles. They found that the presence of the baffle interrupts directly the wall layer interactions and circumferential partitioning of the flow. Therefore, the transport of mass and energy is reduced in comparison to the case with no baffle. The numerical investigations of laminar forced convection in a three-dimensional channel with baffles for periodically fully developed flow and with a uniform

☆ Supported by the King Mongkut's Institute of Technology Ladkrabang research fund, Thailand (KREF015611).
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http://dx.doi.org/10.1016/j.cjche.2014.11.006
1004-9541/

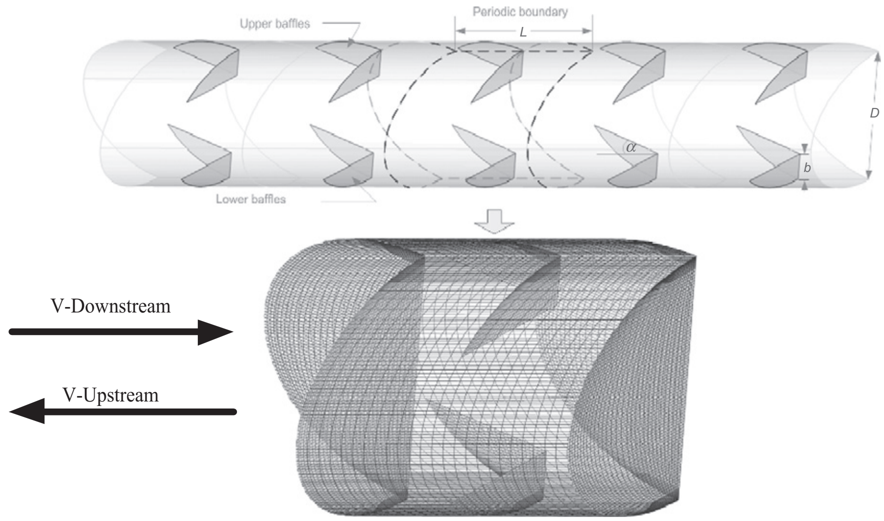

Fig. 1. Tube geometry and computational domain of periodic flow.

heat flux in the top and bottom walls were presented by Lopez *et al.* [8]. Guo and Anand [9] studied the three-dimensional heat transfer in a channel with a single baffle in the entrance region.

Numerical studies for both solid and porous baffles in a two-dimensional channel for the turbulent flow [10] and for the laminar flow regimes [11,12] were conducted, including the report on similar thermal performance. From the experiment for turbulent channel flow with porous baffles of Ko and Anand [13], the porous baffles are found to present a flow behavior as good as the one with solid baffles. Tsay *et al.* [14] investigated numerically by using baffles for enhancement of heat transfer in laminar channel flow over two heated blocks mounted on the lower plate. Sripattanapipat and Promvonge [15] studied numerically the laminar periodic flow and thermal behaviors in a two-dimensional channel fitted with staggered diamond-shaped baffles and found that the diamond baffle with half apex angle of 5–10° performs slightly better than the flat baffle. Promvonge *et al.* [16] also examined numerically the laminar heat transfer in a square channel with 45 degree angled baffle placed on one wall. They reported that a single streamwise vortex flow occurs and induces impinging jets on the wall of the inter-baffle cavity and the baffle trailing edge (BTE) sidewall. Tang and Zhu [17] investigated experimental and numerical for flow of water and heat transfer characteristics in a rectangular channel with discontinuous crossed ribs and grooves. They reported that the overall thermo-hydraulic performance for ribbed-grooved channel is increased by 10%–13.6% when compared to ribbed channel. The effects of wire coil, circular ring and twisted tape on heat transfer and pressure drop were reported [18,19]. The highest thermal enhancement factor was found at 1.42 for combined turbulator, circular ring and twisted tape.

Most of the previous investigations on laminar flow have only considered the heat transfer characteristics for various baffle height and spacing ratios for porous, solid transverse or inclined baffles in a channel. In consequence, the study on V-baffles in circular tube has rarely been reported. In the present work, the numerical computations for three-dimensional laminar periodic circular tube flows over a 45° V-baffle pair mounted on two opposite tube positions are conducted with the main aim to examine the changes in the flow structure and thermal performance. The employment of the V-baffle placed periodically is expected to generate a pair of longitudinal vortex flows along the tube and give better mixing of fluid between the core and the wall region to result in higher heat transfer rate in the tube.

2. Computational Models and Numerical Method

2.1. Computational domain

The system of interest is a circular tube with a 45° V-baffle pair placed on opposite positions of tube wall in tandem for in-line arrangement as shown in Fig. 1. The flow under consideration is expected to attain a periodic flow condition in which the velocity field repeats itself from one cell to another. The concept of periodical fully stabilized flow and its solution procedure have been described in Ref. [20]. The air enters the circular tube at an inlet temperature, T_{in}, and flows over a 45° V-baffle pair where b is the baffle height, D, the tube diameter (0.05 m in this work), and b/D is known as the blockage ratio, B. The axial pitch, L or distance between the V-baffle cells is equaled to D and L/D is defined as the pitch spacing ratio, P. All case studies were present in Table 1.

Table 1
V-baffle tested

Case	Baffle	*P*	*B*	*Re*
I	V-downstream	1	0.10–0.40	100–2000
II	V-upstream	1	0.10–0.40	100–2000

2.2. Boundary conditions

Periodic boundaries are used for the inlet and outlet of the flow domain. Constant mass flow rate of air with temperature of 300 K ($Pr = 0.7$) is assumed in the flow direction rather than constant pressure drop due to periodic flow conditions. The inlet and outlet velocity profiles must be identical. The physical properties of the air have been assumed to remain constant at average bulk temperature. Impermeable boundary and no-slip wall conditions are implemented over the tube wall as well as the V-baffle surface. The constant temperature of circular tube wall is maintained at 310 K while the V-baffle plate is assumed at adiabatic wall conditions.