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Evaluation of mass transport performance in heterogeneous gaseous in-plane spiral reactors with various cross-section geometries at fixed cross-section area

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ABSTRACT

Due to its compactness, high heat and mass transfer rate and ease of manufacture, coiled/spiral tube has been widely used in process industries, especially as heat exchangers and chemical reactors. This study addresses the mass-transport enhancement and reaction performance in in-plane spiral reactor with various cross sections geometries, i.e. circular, half-circular, rectangular, square, trapezoidal and triangular, at fixed cross-section area at several Reynolds numbers. The mass transfer performance is compared with those of straight channel counterpart. Laminar flow of gas with catalytic reactions is investigated using a validated three-dimensional computational fluid dynamics (CFD) model. The results suggest that spiral ducts offer better reaction performance as compared to straight duct, especially at higher Reynolds number. However, it imposes higher pressure drop. Amongst various cross-section, the coil reactor with half-circular geometry yields the highest reaction performance. This study can provide insight for design guidelines of high performance coiled reactor.

1. Introduction

For decades, spiral/coiled ducts have attracted significant attention from researchers world-wide due to their higher heat and mass transfer performance. This higher transfer rate is result of the presence of secondary flow induced by the coil curvature. In addition to their higher transfer rate, their compact structure and ease of manufacture have promoted them to be widely implemented in engineering applications such as heat exchangers, electronic cooling, chromatography, chemical reactor and may other applications. Firstly observed by Dean [1], the presence of secondary flow in coiled duct implies more complicated transport phenomena than those occurring in straight ducts. As a results, numerous experimental [2–6] and numerical [7–12] studies have been conducted and reported, along with reviews of flow and heat transfer characteristics [13,14]. Heat transfer performance of various coil geometries [10] and cross-section [11,12] have been investigated and compared to those of straight duct. Applications of spiral duct design for cooling channel [15] and PEMFC channel [16] have also been investigated and reported.

In chemical engineering field, a study on coiled tubular reactor with circular cross section was conducted and reported by Agrawal and Nigam [17]. By employing first-order reaction kinetics and assuming premix inlet condition, they found that the performance of coiled tubular reactor lies between that of plug and laminar tube flow reactor. Schmidt and Kauling developed an innovative coiled tube reactor for avoidance and elimination of viral contamination [18]. It was found that the reactor is very effective in inactivating critical viruses which lead to minimum product losses. Mandal et al. [19] proposed and investigated innovative coiled flow inverter design reactor for polystyrene synthesis. It was found that monomer conversion in the coiled tube reactor was higher than that of the straight tube reactor. The turbulent forced-convection flow [20] and void-fraction and flow pattern in coiled flow inverter [21] were also investigated by the same research group. This innovative reactor design was also used as inline mixer [22]. Donalson et al. [23] investigated the effect of curvature on the pressure drop of single phase and two-phase flow in serpentine mini channel. The results indicated that the friction factor in the curved serpentine

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geometry lies between conventional theory for straight channel and fully developed flow in helical coil. Eskin [24] developed a model for a gas-liquid bubbly flow in coiled tubing wound on a vertical helical coils. The results indicated that bubble concentration across tubing periodically changes along the coil. Tubing diameter and flow rate significantly affect the bubble concentration variation amplitude. Prasad et al. [25] utilized spiral coil promoters in batch fluidized beds to improve mass transfer performance. It was found that that the mass transfer coefficient increased with increased flow rate and particle diameter. The increased pitch of the coil has decreased the mass transfer coefficient. The increase in coil diameter and diameter of the coil wire has increased mass transfer rates. Renny and Raghavan [26] investigated the residence time, temperature, and processing uniformity in double pipe helical heat exchanger for food processing applications. It was found that residence time distributions and temperature became more uniform with increased flow rates in both the inner and outer tubes.

In our previous work, mixing, heat transfer and reaction performance of microchannel T-junction with coiled channels was numerically investigated [27]. The studied coiled channels were helical, conical and in-plane spirals. The results indicated that coiled channels offer better mixing, heat transfer and reaction performance. In light of the advantages of coiled ducts and few studies on in-plane spiral ducts, it is of interest to study the flow, heat transfer and reaction performance of in-plane spiral ducts with various cross-sections. This paper addresses the heat transfer and reaction performance of in-plane spiral duct with various cross-sections at fixed cross-section area. The investigated cross-section geometries are circular, half circular, rectangular, square, trapezoidal and triangular. The performance will be compared to those of straight ducts. The objective is to obtain optimum design of spiral reactors where the cross-section area is fixed in order to improve catalyst utilization and save the amount of precious catalyst coating.

The layout of the paper is as follows. First, the mathematical model which comprises conservation equation of mass, momentum, energy and species together with constitutive relations and chemical reactions is introduced. The mathematical model is then implemented numerically utilizing finite-volume-based CFD tools Fluent 6.3.26. To assess the heat transfer and reaction performances, a concept figure of merit will be introduced and implemented. Parametric studies are then conducted to evaluate the effect of several parameters to the heat and reaction performance. Finally, summary and conclusion are drawn based on the presented results. Advantages and limitations of the reactor design will be highlighted.

Table 1
Geometric and parameters.

Parameters	Value	Unit
L	1.2	m
w	2×10^{-2}	m
$R_{c,i}$	2×10^{-2}	m
$R_{c,o}$	9×10^{-2}	m
d_C	1.13×10^{-2}	m
r_{Hc}	7.98×10^{-3}	m
w_R	1.6×10^{-2}	m
h_R	6.25×10^{-3}	m
w_S	1×10^{-2}	m
w_{Tp1}	7×10^{-3}	m
w_{Tp2}	1.3×10^{-2}	m
h_{Tp}	1×10^{-2}	m
w_{Tr}	1.6×10^{-2}	m
h_{Tr}	1.25×10^{-2}	m

2. Mathematical formulation

The studied reactors comprise straight and in-plane spiral reactor with various cross-sections: circular, half circular, rectangular, square, trapezoidal and triangular. Their schematic representation is presented in Fig. 1 while the details of their geometric parameters are summarized in Table 1. The cross-section areas for all configurations are identical. We assume premix inlet condition [28]. The reaction occurs at the reactor wall. The flow is assumed to be steady. The studied fluid is Newtonian fluid. Only laminar flow is considered in this study.

3. Governing equations

The conservation equations for mass, momentum and energy for the flow inside the ducts are given by [27–29]:

$$\nabla\cdot\rho\mathbf{u}=0, \tag{1}$$

$$\nabla\cdot(\rho\mathbf{u}\otimes\mathbf{u})=-\nabla p+\nabla\left[\mu(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)-\frac{2}{3}\mu(\nabla\cdot\mathbf{u})\,[\mathbf{I}]\right], \tag{2}$$

$$\nabla\cdot(\rho\mathbf{u}\omega_i)=\nabla\cdot(\rho D_i\nabla\omega_i)+R_i, \tag{3}$$

$$\nabla\cdot(\rho c_p\mathbf{u}T)=\nabla\cdot(k_{eff}\nabla T)+S_{temp}, \tag{4}$$

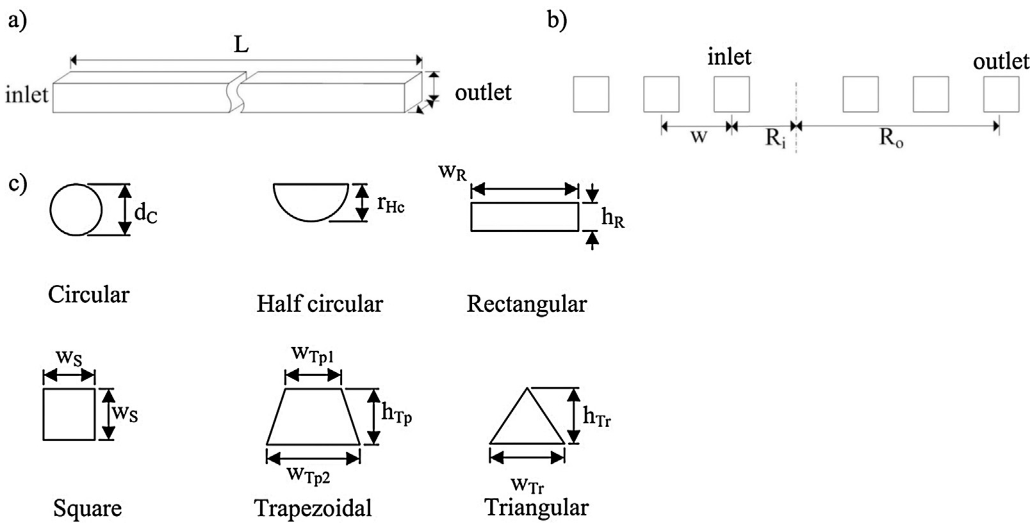

Fig. 1. Schematics of (a) straight duct with square cross-section, (b) spiral duct with square cross-section and (c) various cross-sections for both straight and spiral ducts.