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Prediction of hydrodynamic entrance length for single and two-phase flow in helical coils

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ABSTRACT

The hydrodynamic entrance length in helical coils for single and two-phase bubbly flow was studied experimentally and numerically. Development region length and the detailed characteristics of fluid flow have been investigated by varying helical coil parameters such as tube diameter, coil diameter and void fraction. For the CFD simulation of the two-phase fluid flow, the Eulerian–Eulerian model was employed. To calculate the turbulent fluctuations, the SST$^{k-\omega}$ turbulence model has been used. The experimental and numerical simulation of the local parameters demonstrates that the hydrodynamic developing length (L/D) increases when Reynolds number increases in the single and two-phase flows. The obtained results show that the development entrance length increases with the increase of pipe diameter and decreases with the increase of coil diameter. Also, entrance length decreases while curvature ratio of helical coil and void fraction increase. A correlational equation has been suggested to predict the hydrodynamic entrance length as functions of various parameters of the helical coil.

1. Introduction

Helical coils and curved tubes have a vast range of application. They are used in the food industry, nuclear reactors, chemical processing, heat recovery systems, power plants and medical equipment [1–6]. Some of the helical coils are required high flow rate. Study of different parameter is important for the design of pressure drop and heat transfer in helical coils. Common applications include evaporators, boiler design, condensers, air conditions and several industries such as oil, heat exchangers, petrochemical, chemical plants, fluidized bed combustors, oil wells and pipelines [7–9]. In low void fraction, the pattern of dominant flow is bubbly flow. In various industries (bubble column reactors, oil transportation, nuclear cooling systems, mineral separation), void fraction parameter in two-phase bubbly flow is required for hydrodynamic and thermal design. When a fluid flows through a helical pipe, it is subjected to a centrifugal force. The centrifugal force causes the secondary flow that accounts for the increase in axial flow velocity near the outer wall of the tube. Dean [10], for the first time, discovered a secondary flow inside the curved pipes and introduced a dimensionless parameter to express this type of flow, known as the Dean number. Bara et al. [11] showed that by increasing of the Dean number, the boundary layers of the secondary flow become thicker and then the two vortices system divides into four vortices in a curved duct of a square cross section. Berger et al. [12] also showed that the boundary layer thickness decreases with the increase of the Dean number. Moll et al. [13] showed that shear stress caused by the formation of a secondary flow in helical tubes increased at the tube wall. Also, they found that the permeation is improved depending on the operating parameters.

The positive effect of the curving on the flow's characteristic and heat transfer has also been reported [14–16]. It was found that a secondary flow has a positive effect on the efficiency of the heat and mass transfer. Huttl et al. [17,18] numerically studied the influence of curvature and torsion on fully developed turbulent flow characteristics in a curved and helically coiled pipe and showed that the torsion effect is weaker than the curvature effect. The effect of curvature and torsion on the flow in a helical pipe was numerically studied by Wang [19]. He found that both curvature and torsion induce non-negligible effects when the Reynolds number is less than approximately 40. Joseph et al. [20] using the numerical solution of the curved square pipe came to the conclusion that the two-vortex systems can be divided into four zones.

Murai et al. [21] have experimentally studied the pattern of two-phase of air–water. Effect of centrifugal acceleration on flow

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Nomenclature

A	inner radius of the tube, m
D	tube diameter, m
D_c	pitch circle diameter of coil, m
De	Dean number
Eo	Eotvos number
F	force term, N
G	gravity acceleration, m/s^2
H	tube pitch, m
P	pressure, Pa
R_c	pitch circle radius of coil, m
Re	Reynolds number
S	source term
U	velocity, m/s
u_{ave}	average velocity, m/s
V	volume, m^3

Greek letters

α	void fraction
δ	curvature ratio
μ	dynamic viscosity, kg/m s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
φ	helix angle

Subscripts

L	liquid phase
Lg	from phase l to phase g
G	gas phase
K	phase (liquid or gas)
M	mixture
Pq	from phase p to phase q
TD	turbulence dissipation
Vm	virtual mass

patterns were studied; and flow structure temporal and spatial distribution was extracted while three types of flow regimes were observed. Vashisth et al. [24,25] investigated the local variables and interfacial phenomena for two-phase flow in a coiled tube using the Volume Of Fluid (VOF). The results showed that the curvature of the coil causes substantial symmetry in the radial distribution of the main flow velocity. Also, they showed that by increasing the Dean number ($De < 700$), the entry length increases. Two-phase frictional pressure drop of gas-non-Newtonian liquid flow in vertical helical coils was studied by Biswas and Das [27]. They investigated the effects of coil diameter and flow properties on the two-phase pressure drop. The same result has also been verified by [28]. The rate of the liquid–solid mass transfer process in helical coils was studied by Abdel-Aziz et al. [29].

Lin and Ebadian [30] studied the effects of inlet turbulence on the development turbulent flow in the entrance region of a helically coiled pipe with the $k-\varepsilon$ standard model and found that bulk temperature kinetic energy for the entrance was not affected by the inlet turbulence level. Also, Lin et al. [31] numerically investigated the laminar flow and the heat transfer in the entrance region of helical pipes. Kumar et al. [33,34] investigated and numerically modeled the hydrodynamics and heat transfer characteristics of a heat exchanger under laminar and turbulent flow conditions. Their numerical results for friction factor and Nusselt number were reasonably in good agreement with the relations of other researchers. Mridha and Nigam [35] numerically studied the hydrodynamics and heat transfer of turbulent forced convection in helical heat exchanger coils with circular cross section.

Springer et al. [36] numerically studied the developing length of tori and woven tubes in the Reynolds number less than 400 ($Re < 400$). Austin and Seader [37], based on the work of Keulegan and Beij [38] empirical relation, presented the entrance angle based on Dean number and curvature ratio (Eq. (1)).

$$\theta = 49\left(\frac{De}{R_c}\right)^{1/3} \qquad 198 < De < 948 \quad (1)$$

The development of a flow in a torus was studied by Gaun and Martonen [39,40]. They used FIDAP software for the numerical solution and their relationship in the range of Dean number is 10–250 (Eq. (2)).

$$\frac{L_{DS}}{L_{DT}} = \sqrt{\delta}\left(-1.5 - 2.40\times10^{-4}De^2 + 8.42\times10^{-2}De + \frac{41.9}{De}\right) \quad (2)$$

Ghasemi et al. [41,42] thoroughly studied different RANS models to investigate their accuracy in predicting the entropy generation in a transitional boundary layer region. They results shows that $k-\omega$ models predicts the energy loss much better that the other models as they compared the results with their DNS and analytical method. Saffari et al. [43] investigated optimization of heat transfer and pressure drop for spiral heat exchanger and they suggested a relation for pressure drop and heat transfer. Also, Saffari et al. [44] investigated the effect of bubble on pressure drop reduction in helical coils.Their results indicate that drag reduction of up to 25% can be calculated in helical coils with injection bubbles.

Review of the literature shows that the equations for development length in the previous works have been proposed for torus and helical tube in the low Reynolds numbers and laminar flows. Based on our knowledge, the development entrance length has not been studied for single and two-phase turbulent flow in helical coil. Therefore, this paper investigated the entrance length of helical coil experimentally and numerically for single and two phase flow. In this analysis, computational fluid dynamics (CFD) and two-phase Eulerian–Eulerian in OpenFOAM code were used. Also, a relation for entrance length of turbulent flow in single-phase and two-phase flow (air–water) in the helical tube based on the Reynolds number, Dean number, curvature ratio and void fraction was proposed.

2. Experimental setup

A schematic diagram of the empirical circuit for measuring the pressure drop inside the helical coils is shown in Fig. 1. The test circuit used here is explained in the following section based on previous works [44–46]:

- Centrifuge pumps for the circuit water with maximum mass flow rate of 6 kg/s.
- Flow meter of water: an inductive type was used to measure and adjust the water flow in the circuit. Water flow rate is %1 in relative error.
- Air flow meter and valve for measuring and regulating the air flow rate inlet. The uncertainty of air flow rate is 0.1 according to air flow meter.
- Water and bubble separating tank with 0.8 m diameter, 3 m height and water capacity of 1.5 m^3. There is a filter in the entrance of the tank which causes the separation of the bubbles from the water and just the single phase fluid of water remains inside the tank.