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The effect of bubble on pressure drop reduction in helical coil

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ABSTRACT

In the present paper, the effect of bubbles on the pressure drop and drag reduction of air–water two phase flows in vertical helical coils was experimentally investigated. The curvature ratio of the studied coils was 0.06 and 0.095. The ranges of the investigated Reynolds numbers and void fractions were 8000–50,000 and 0–0.09, respectively. The effect of the drag reduction will decrease with the increase of Reynolds number and the amount of drag reduction increases with increasing void fraction. It was found that for helical coil, the drag reduction increases with the decrease of curvature because of the secondary flow increases with the increase of curvature. The average diameter of injected bubbles was 270 μm; and as the Reynolds number increased, the diameters of injected bubbles diminished. The experimental results indicate that in this range of void fraction, the maximum reduction of friction drag is 25%, which occurs at low Reynolds numbers. Also, in void fraction 0.01 the drag reduction was 9% which was observed in Reynolds of 11,000.

1. Introduction

Two-phase flows inside helical tubes have numerous applications in, such as, heat exchangers, chemical and atomic reactors, boilers, food industries, cryogenic industries and refineries. [1–5]. The curvature of these coils produces a centrifugal force and this force leads to the increase of pressure loss relative to flows in straight tubes. For this reason, several methods of drag reduction have been proposed and investigated in the last decade. The injection of dissolvable polymers and particles has been one of the applied methods of friction drag reduction [6–11]. Another technique for reducing frictional losses is the injection of microbubbles, which has attracted a lot of attention these days and a considerable number of research has been carried out on this subject in order to understand the mechanism of drag reduction and also the effects of various parameters on it. The undefined movement of bubbles within the flow greatly affects the flow momentum and the heat and mass transfers within it; and several research works have been conducted on these issues [12–16]. Most of the studies on the drag reduction by microbubbles have been conducted on flat plates [17,18] and inside a channel [19,20].

The unidentified movement of the bubble in the helical flow has great influence on the momentum of the flow, the thermal and mass transfer, and there have been several studies conducted in this field [9,10,21]. Many numerical and experimental studies have been performed on the turbulent boundary layer through the injection of microbubbles [22–24]. McCormick et al. [25] reported the first observations of frictional drag reduction on a round submerged body, which was achieved by using the microbubbles of hydrogen obtained from electrolysis. They showed that with the increase of electrical current and, consequently, the production of more bubbles, the amount of drag diminishes. The injection of gas through a porous material for the reduction of frictional drag in a rectangular channel flow has been investigated by Bogdevich et al. [26]. They discovered that the amount of skin friction reduction has a significant and direct relationship with the void fraction of injected air bubbles and concluded that the amount of drag diminishes with the increase of void fraction. Madavan et al. [27] measured the amount of drag reduction inside a rectangular channel for high flow speeds. Also, Madavan et al. [27] and Marie [28] simulated a model for the effect of bubbles concentration based on viscosity and density. They demonstrated that kinematic viscosity increases with the injection of bubbles.

Deutsch and Castano [29] studied the reduction of drag by means of microbubbles for a submerged axisymmetric object and showed that the amount of drag reduction diminishes with the increase of free-stream. Moriguchi and Kato [33] and Hassan et al. [34] investigated the effect of the mean volume fraction of bubbles on flow modification, and discovered that with the increase of the mean volume fraction, the amount of drag is reduced. Guin [35] demonstrated that the reduction of drag is dependent on how and where the bubbles concentrate inside the flow and also on the diameter of bubbles. The experimental tests of Murai et al. [36] in a horizontal channel showed that, for the reduction of drag, bubble diameter has a significant effect on the shear layer. They realized that when the bubble diameter is larger than the boundary layer thickness, the friction coefficient decreases. Merkle and

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Deutsch [37] concluded that there is no specific bubble diameter for the reduction of drag. They found out that the diameter of bubbles should be larger than the viscous sub-layer and smaller than the boundary layer thicknesses. Shen et al. [38] performed experimental tests on a certain range of bubble diameters for the reduction of drag and concluded that bubble diameter has no effect on drag reduction.

Kunz et al. [39] presented a model for the formation and breakup of microbubbles. In their model, the dynamics of interfacial forces and the formation and breakup of bubbles play important roles. Lu and Tryggvason [40] numerically studied the bubbly turbulent flow in a vertical channel using the control volume method. They observed that the volume fraction profile greatly depends on the formability of the bubbles. An experimental investigation of microbubbles two-phase flows in vertical pipe has been studied by Wedin et al. [41]. Their results showed that symmetrical void distributions with clear accumulations near walls. In the same laboratory and using the same experimental circuit, Nouri et al. [42] have studied drag reduction inside the vertical direct tube by injecting microbubbles. Their results indicate that drag reduction of up to 35% can be calculated.

It should be noted that most of the previous research works on drag reduction have involved the injection of bubbles over flat plates and in straight channels and tubes; and no specific work has been carried out for the reduction of frictional drag in coiled tubes by using bubbles. In this article, the effects of drag reduction and pressure loss by means of microbubbles injection in a vertical helical coil have been experimentally investigated for the bubbly flow, up to the Reynolds number of 50,000.

2. Experimental setup

Fig. 1 shows the schematic diagram of the empirical circuit for measuring the pressure drop inside the helical coil. The test circuit used here includes the followings: A transparent helical and straight tube has been used both in order to observe the flow and to take photographs.

- Centrifuge pumps for the circuit water with maximum mass flow rate of 6 L/S.
- Bubble and separating tank with 80 cm diameter, 3 m length and 1.5 m^3 capacity. 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.
- Flow meter of water: an inductive type was used in order to measure and adjust the water flow meter in the circuit. It should be noted that the error of flow meter was 0.01.
- Air flow meter and valve for measuring and regulating the air flow rate inlet and the bubble generator (with approximate error of 0.001).
- Pressure sensors: used to measure pressure drop. Being connected to a pressure box and a computer, these sensors digitally calculate the pressure difference. Pressure sensor was of the type of HONEYWELL differential pressure sensors. Using “Data Acquisition” software with the speed of 1000 samples per second for real-time data acquisition from the sensors was performed. The calculation error of pressure drop and frictional coefficient are 1.5% and 2%, respectively.
- Air compressor with maximum pressure of 0.8 MPa for producing air and bubble.
- A camera with high shutter speed and 3 projectors for lighting.
- A bubble generator apparatus: the apparatus and its application have been described in previous works [42,43]. In this set, the output water of the pump enters the bubble's generators through the provided angular nozzles. These nozzles, which have been placed on the lower flange of the bubble generator, insert the water into the housings with a 90-degree angle to the vertical axis. This caused a rotating and vortical motion of the flow and increases the shear and turbulence stresses of the flow. In this apparatus, the compressed air, enters the bubble generator housing with 12 input nozzles and enters radial which coincides with the injected water flow from 6 nozzles. The air nozzles in two rows and 6 sections with equal intervals are devised on the collector's circumference. These two rows of air nozzle are 1 cm far from each other. When air bubbles into the collectors they are affected by the Reynolds stresses and shear stresses will cause air bubbles to break. Air bubbles divide into several smaller portions and flow towards the collector's exit.

In this circuit, through the collector's exit, the fluid flow along with the generated microbubbles enter the 50-cm long vertical transparent tube which is the entrance of the helical tube.

3. Measuring the drag reduction and pressure drop

A schematic view of the experimental apparatus used for measuring drag reduction and pressure drop has been shown in Fig. 1.

In this study, two helical coils with different curvature ratio have been investigated. The inside diameters of the helical tubes are 12 and 19 mm and the coil diameter is 200 mm. The curvature ratios are 0.06 and 0.095, respectively, and each coil has 5 turns. The pitch of each coil is 24 mm. Although when the coil pitch is smaller than the coil diameter, it does not have much influence on the pressure drop [30]. The geometrical parameters and specification of the investigated coils have been given in Fig. 2 and Table 1. The pressure drop has been measured with the incoming air flow rate being zero (single-phase flow). In this case, the pressure loss and the friction coefficient have been evaluated for both coils at different Reynolds numbers. The pressure tapes at the test were attached at the two points on the helical tubes at the axial direction. The two tapes installed to insure that the measure pressure drop is in the fully developed region. The pressure difference along the vertical helical tube equals the sum of hydrostatic pressure resulted from the fluid column and the required pressure to overcome the frictional drop. Then the static pressure is subtracted from the total and just the frictional pressure drop is reported.

4. Results of single-phase flow in helical coil

The following equation was used to calculate the friction factor in coiled tubing:

$$f = \frac{\Delta p d}{2L\rho V^2} \tag{1}$$

In this equation d is the tube inner diameter, L the helical tube length, ρ the fluid density, and V is flow mean velocity.

Empirical equation for the friction factor in helical coiled is provided.

Mishra and Gupta equation for turbulent flow in the helical tube [30]:

$$f_{ct} = \frac{0.0791}{\mathrm{Re}^{0.25}} + 0.0075\delta^{0.5} \quad 6.7 < D/d < 346 \quad 0 < H/D < 25.4 \quad \mathrm{Re}_{crit} < \mathrm{Re} < 10^5 \tag{2}$$

Also, Ito proposed the following equation for spiral pipe friction factor [31]:

$$f_{ct} = 0.076\mathrm{Re}^{-0.25} + 0.00725\left(\frac{d}{D}\right)^{1/2} \tag{3}$$