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Two-phase flow pattern in small diameter tubes with the presence of horizontal return bend

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Abstract

This study provides a qualitatively visual observation of the two-phase flow patterns for air-water mixtures inside 6.9, 4.95, and 3 mm smooth diameter tubes with the presence of horizontal return bend. The influence of the return bend on the two-phase flow patterns are investigated. For $D = 6.9$ mm and at a mass flux of 50 $\mathrm{kg\,m^{-2}\,s^{-1}}$ having a quality less than 0.1, no influence on the flow patterns is seen at a larger curvature ratio of 7.1. However, were the curvature ratio reduced to 3, the flow pattern in the recovery region is temporarily turned from stratified flow into annular flow. The temporary flow pattern transition phenomenon from stratified flow to annular flow is not so pronounced with the decrease of tube diameter. It is likely that this phenomenon is related to the influence of surface tension and the reduction of developing length of the swirl flow. Based on the present flow visualization, three flow pattern maps are proposed to describe the effect of return bend on the transition of two-phase flow pattern.

Keywords: Return bend; Two-phase flow pattern

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1. Introduction

U-tube or return bend are extensively used in compact heat exchangers, boilers, refrigerators, chemical plants, as well as the food, drug, and cryogenics industries. Either single-phase or two-phase flow can occur in the applications. For single-phase flow, extensive studies were carried out numerically and experimentally by various investigators. With the presence of return bend, the centrifugal force drives the more rapid fluid in the concave part of the curve channel while the fluid in the convex parts is slowing down which results in the consequence of a secondary flow at right angle to the main flow [1]. The induced flow disturbance causes extra pressure loss when comparing to that of a straight tube [2–4]. The magnitude of such secondary flows obviously reduces with an increase of bend radius, and with a decrease of fluid velocity. Dean also proposed a parameter to consider the dynamic similarity for steady laminar flow in a curved tube, which is now called the Dean number ($D_N = Re_D(2R/D^{0.5})$), where D is the tube inside diameter and R is the curvature radius. Furthermore, when the Dean number exceeds a critical value, a secondary vortex pair with counter-rotating circulation is found near the outer wall [5].

Converse to that of single-phase flow, literatures concerning the two-phase flow are comparatively rare. Most of the published literature were related to the helical coil and wavy pipe. Quantitatively, the flow pattern observed for the gas–liquid two-phase flow in upward helical coils are similar to those seen in horizontal straight tubes [6,7]. Chen and Zhang [7] also proposed three criteria for predicting the flow pattern transitions in upward helical coils. Awwad et al. [8] conducted

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Nomenclature

D	inside diameter of the tube, m
G	mass flux, $\mathrm{kg\,m^{-2}\,s^{-1}}$
R	curvature of the return bend, $\mathrm{m\,s^{-1}}$
U_{GS}	superficial velocity, gas phase, $\mathrm{m\,s^{-1}}$
U_{LS}	superficial velocity, liquid phase, $\mathrm{m\,s^{-1}}$
x	vapor quality

Greek symbol

ρ	density, $\mathrm{kg\,m^{-3}}$

Subscripts

L	liquid phase
G	gas phase

air–water two-phase flow in horizontal helicoidal pipes ($D = 25.4$ mm, $2R/D = 13.8$ and 25.6). It was found that the pipe and coil diameters have certain effects in low rates of flow. For practical application of compact heat exchanger, the tube diameter is usually less than 10 mm. The influence of surface tension becomes comparatively large. The observed flow patterns differ greatly from those of the horizontal straight tube because of the influence of gravity acting on the up and down fluid. Further, the helicoidal coil is in fact quite different from the 180° return bend in this study because the disturbance occurs discontinuously only at the return bend. Thus, the upstream and downstream nearby the return bend is expected to be influenced.

In view of the lack of relevant investigations of the basic aspect of the two-phase flow characteristics in the presence of the 180° return bend. The purpose of this study is therefore to investigate the two-phase flow patterns with the influence of return bend subjected to various radius of curvature. Attempts will be focused on developing appropriate two-phase flow regime map and their transitions.

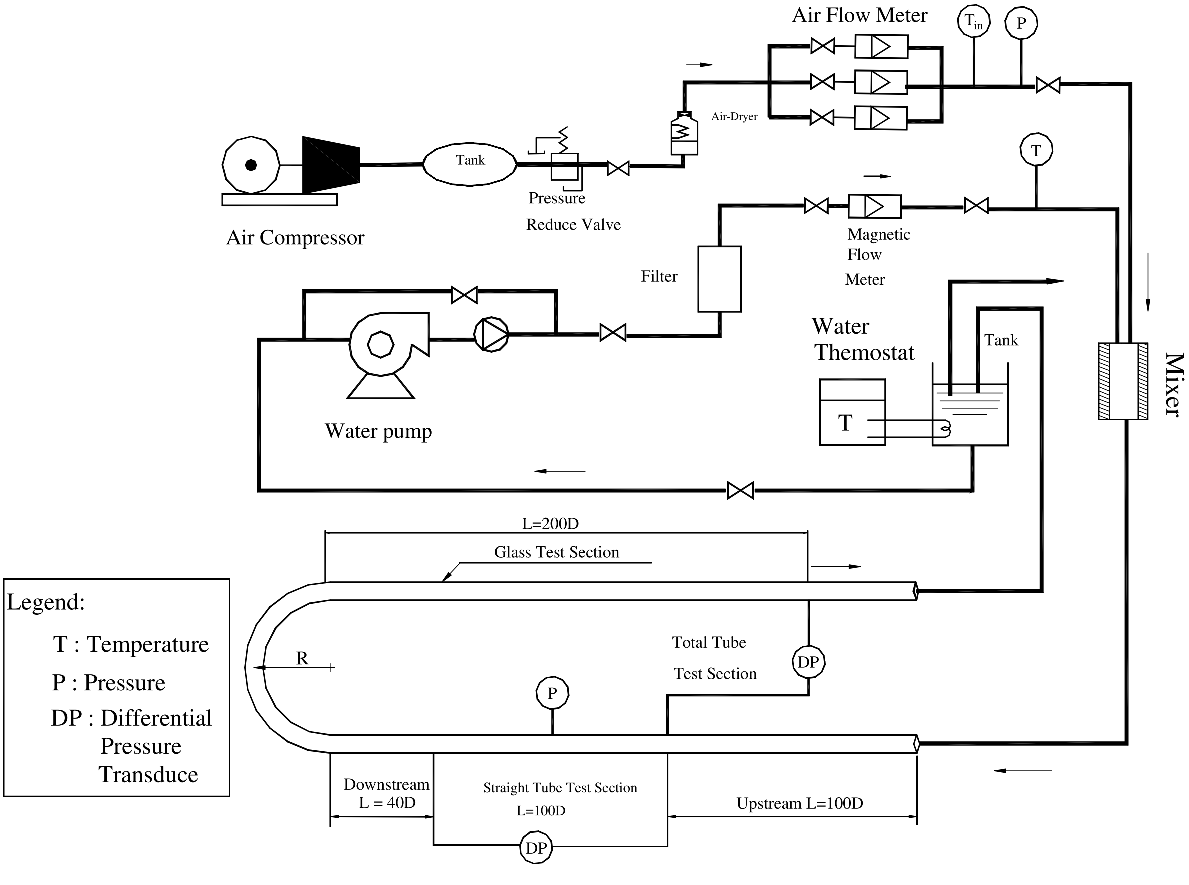

Fig. 1. Schematic of the test facility.

2. Experimental setup

The test rig is designed to conduct tests with air–water mixtures shown in Fig. 1. Air is supplied from an air-compressor and then stored in a compressed-air storage tank. Detailed description of the experimental facility and related validation of the experimental setup can be found from previous studies [9–11]. A total of nine tubes having different curvature ratios are used for testing. The test tubes are made of glass tube having inner diameters of 6.9, 4.95 and 3 mm. Notice that all the experiments of the test tubes were conducted horizontally. However, photos were taken from the side view and from the top view simultaneously. Further relevant geometries like radius of the return bend, length of straight tube test tube, and total length of test tube are tabulated in Table 1.

3. Results and discussion

In a general discussion of the two-phase flow pattern subjected to the influence of return bend, one can see the schematic of Fig. 2. Two-phase flow across the test tube can be roughly classified into five regions which include the (I) upstream region; (II) de-accelerating region; (III) return bend; (IV) recovery region; and (V) downstream region. Notice that the length of region (IV) is longer than that of region (II). The lengths of regions (II) and (IV) varies with flow patterns. At the upstream and downstream region, the flow patterns can be regarded as that of a typical straight tube. The return bend section (III) tends to slow down the air flow while the liquid is forced towards the concave portion of the return bend due to centrifugal force. As a consequence, the apparently slowing down motion of the airflow in the return bend acts to de-accelerate the two-phase motion in region (II). This is because the significant difference of density ratios of air–water mixtures that give rise to a very large void fraction. Leaving the return bend section, the flow is recovered in the (IV) region.

Photographs that are representative of the observed flow patterns for $D = 6.9$, 4.95, and 3.0 mm correspond to mass flow fluxes from 50 to 700 $\mathrm{kg\,m^{-2}\,s^{-1}}$ are examined. Fig. 3 presents the typical photos showing the

Table 1
Relevant geometrical parameters of the test tubes

D (diameter mm)	R (center to center)	$2R/D$	Length of pressure tap	
			Straight tube	Total tube length
3	9.6	3.2	300	$330D + \pi D/2$
	15	5		
	21	7		
4.95	15	3.03	500	
	25	5.05		
	35	7.07		
6.9	21	3.04	700	
	35	5.03		
	49	7.1		

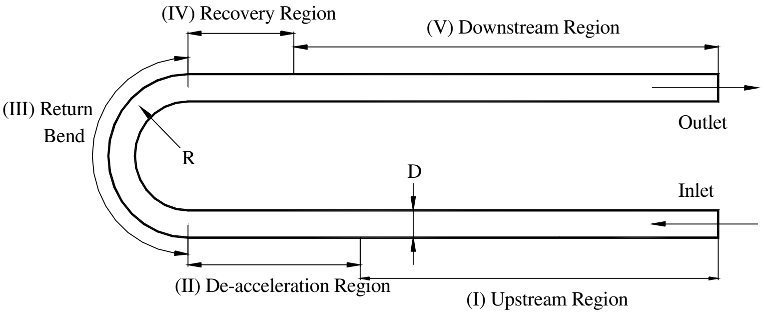

Fig. 2. Schematic of the flow regime with the influence of return bend.

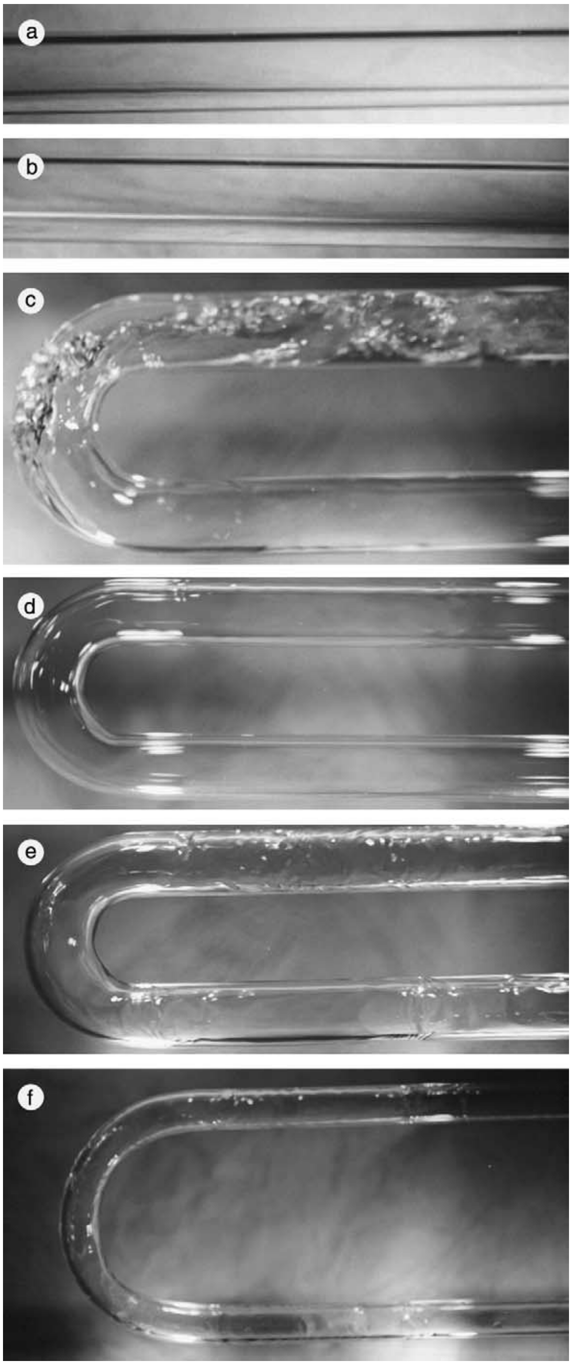

Fig. 3. Flow pattern for $G = 50\ \mathrm{kg\,m^{-2}\,s^{-1}}$ for $D = 6.9$ mm having $2R/D = 3$ and 7.1.

influence of return bend for $D = 6.9$ and 3 mm. For $D = 6.9$ mm at a mass flux of $50\ \mathrm{kg\,m^{-2}\,s^{-1}}$ and a quality of 0.1, as schematically illustrated in Fig. 3a and b, both the upstream and downstream section shows a tranquil stratified flow. However, with the presence of return bend having $2R/D = 3$, the flow pattern shown in Fig. 3c reveals a pronounced change in the return bend and the recovery section. The liquid in the bottom is swirled along the concave part of the return bend while the air flow is forced towards the convex portion of the return bend. The swirled motion continues in the recovery region (IV) due to its inertia and the secondary flow motion. The flow pattern in region (IV) was observed to temporarily turn into annular flow. The temporarily annular flow eventually returns back to the stratified region in the downstream region. However, for $2R/D = 7.1$ at the same quality, the temporarily annular flow pattern is not observed.

It is interesting to know that a further increase of the quality to 0.3 for $2R/D = 3$ (Fig. 3d), the flow pattern in the return bend (actually applicable to the whole test tube) becomes stratified flow again. This is because that the quantity of the liquid flow is reduced and the inertia of liquid secondary force was unable to overcome the higher gas inertia force for overturning the liquid to reach the top portion of the tube to become annular flow pattern. A further increase of quality to 0.4 (Fig. 3e), the annular flow pattern prevails throughout the tube for both $2R/D = 3$ and $2R/D = 7.1$. One can see that the recovery section process a comparatively wavy film than that in the region (II). This is influenced by the return bend. For a higher mass flux like $400\ \mathrm{kg\,m^{-2}\,s^{-1}}$, the major flow pattern for $x > 0.02$ is annular flow in every region of the test tube for both $2R/D = 3$ and 7.1 (see Fig. 3f).

Converse to the visual results of $D = 6.9$ mm, at a smaller tube diameter of 3 mm as shown in Fig. 4, one can find that the change from stratified flow pattern to annular flow pattern at region (IV) subjected to the influence of return bend is less pronounced. There are two explanations for this phenomenon. Firstly, the existing region of the stratified flow pattern decreases at a smaller diameter tube [12] due to the smaller effect of the gravity whereas the influence of surface tension is comparatively large. This may lead to the reduction of the liquid over-turn phenomenon. Secondly, for a given curvature ratio, the length of the return bend of a larger diameter is much longer than that of a smaller diameter tube. In this regard, the swirled motion of the smaller diameter tube may not overturn the liquid after the return bend because the lack of developing length. Therefore, one can experience the change of stratified flow pattern to annular flow pattern after the return bend is less pronounced.

Based on previous discussions, the influence of the return bend on the two-phase flow transition is two folds. Firstly, for $D = 6.9$ mm at a low mass flux region like $G = 50\ \mathrm{kg\,m^{-2}\,s^{-1}}$, the presence of return bend may change the stratified flow pattern shortly

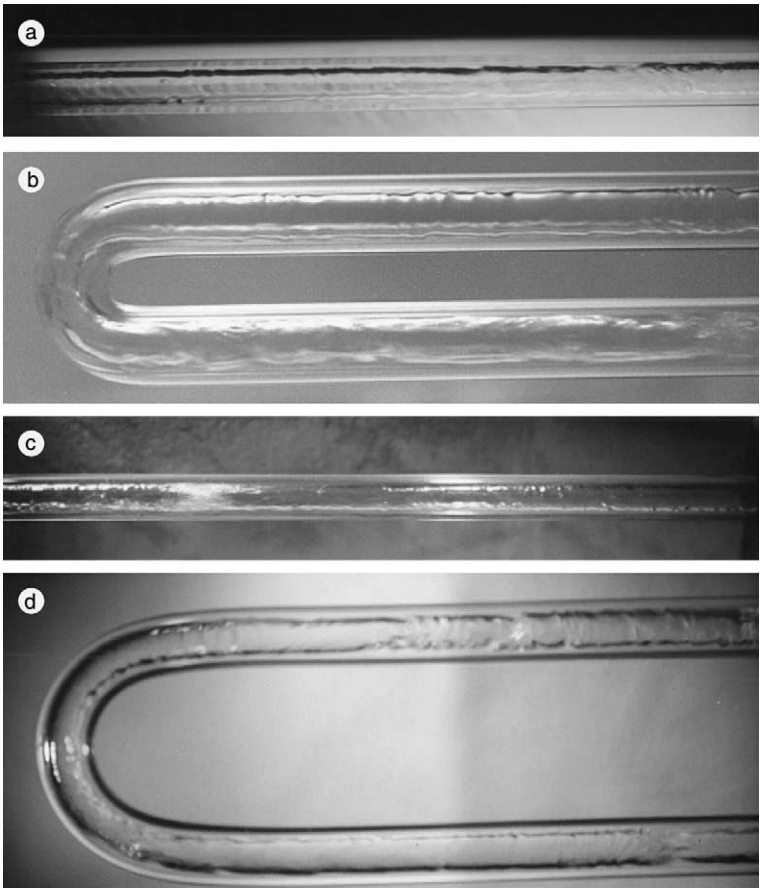

Fig. 4. Flow pattern for $G = 200$ kg m^{-2} s^{-1} for $D = 3$ mm having $2R/D = 3.2$ and 7.

into annular flow region at region III. However, this effect becomes less pronounced as the curvature ratio is increased or the tube size is reduced. A quantitative description of this influence is shown from the proposed flow pattern map in Fig. 5 for $D = 3$, 4.95, and 6.9 mm. Notice that the dispersed flow region is based on the boundary line from Coleman and Garimella ([12], $D = 5.5$ mm) because the limitation of the present test facility.

4. Conclusions

Visual observation of the two-phase flow patterns for air–water mixtures inside smooth tubes a 3, 4.95, and 6.9 mm diameter tube with curvature ratios of 3, 5, and 7 are reported in this study. The range of mass flux is between 50 and 700 kg m^{-2} s^{-1}. Based on the previous discussion, the following conclusions are made:

(1) For $D = 6.9$ mm and at a mass flux of 50 kg m^{-2} s^{-1} having a quality less than 0.1, no influence on the flow patterns is seen at a larger curvature ratio of 7.1. However, were the curvature ratio reduced to 3, one can seen the flow pattern in the recovery region is temporally turned from stratified flow into annular flow. But this phenomenon is suppressed again when the quality is increased to 0.3 due to the lack of liquid portion. For a quality larger than 0.4, the annular flow pattern prevails in the entire tube.

(2) For a smaller diameter tube of $D = 3$ mm, the flow pattern is different from that of $D = 6.9$ mm. One of the major distinctions for $D = 3$ mm relative to that of $D = 6.9$ mm with the presence the return bend is the less pronounced change from stratified flow pattern to annular flow pattern. This phenomenon is likely related to (1) the relative increase of the surface tension; and (2) the lack of developing length of the swirled flow to over-turn the liquid.

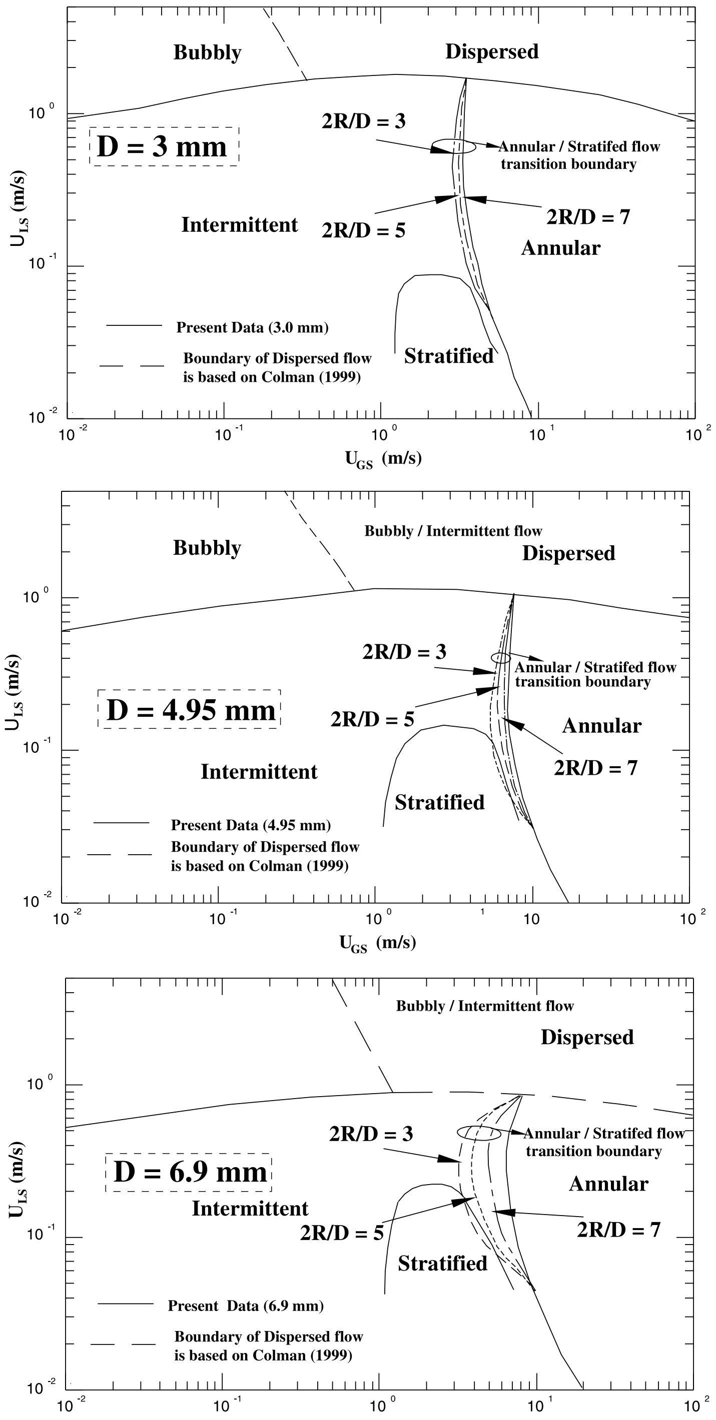

Fig. 5. Proposed two-phase flow pattern with the influence of return bend for $D = 3$, 4.95, and 6.9 mm.

(3) Based on the present flow visualization, flow patterns for $D = 3$, 4.95, and 6.9 mm are proposed to describe to effect of return bend on the transition of two-phase flow pattern.

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