



Experimental Examination of Gas-liquid Two-phase Flow Patterns in an Inclined Rectangular Channel with 90° Bend for Various Vertical Lengths

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A B S T R A C T

In order to realize the behavior of two-phase flow in an inclined rectangular channel with 90° bend for various vertical lengths, an experimental investigation has performed. The test section (a channel with 30 m length) contains two horizontal parts and a middle vertical section. Three vertical lengths of 50, 100 and 150 cm were utilized along the test section. The cross section of the rectangular channel is 10 cm × 15 cm. Air and water were the fluids used in this work. Various flow patterns are created by varying the volumetric flow-rates of gas and liquid; the air and water flow rates were in the range of 2 to 10 m³/h and 34 to 235 m³/h, respectively. The high speed video system was utilized to achieve image subsequence of the flow under various conditions. The effects of vertical length on flow regimes and pattern transition borders are examined. According to the flow visualization, no vortex was observed in the vertical section. The significant flow regime in the vertical section is churn flow regime. It is concluded that the flow pattern structures are not greatly affected by changing the vertical length.

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1. INTRODUCTION

Two-phase flows are of considerable interest to many industries such as power generation, thermal hydraulic reactor system, chemical plants and food production. The two-phase flow in a rectangular channel has attracted special research interest in recent decades owing to its numerous applications such as in plate type nuclear fuels [1–3], high performance micro-electronics [4, 5] and polymer melt filling process [6–8].

In the previous decades, many researchers have concentrated on comprehensive two-phase flow treatment utilizing experimental system and modeling numerical methods. However, most of these studies are focused on two phase flow in horizontal and vertical systems with little consideration given to this phenomenon in different pipe inclinations between horizontal and vertical. Regarding to the great utilization of pipe lines transferring two-phase flow in chemical and petroleum equipments, it is necessary to investigate the effect of channel inclination on the two-phase flow cases.

When two-phase flows move along a pipe or channel, various flow patterns can be created, affected by different variables. Many flow patterns have been investigated by number of researchers in horizontal, vertical and inclined pipes or channels. Wilmarth and Ishii [9, 10] perceived the flow patterns and measured the void fraction and the interfacial area concentration of adiabatic co-current vertical and horizontal air-water flow in narrow rectangular channels with gaps of 1 and 2 mm. Nguyen [11] and Beggs [12] examined two-phase flow pattern, pressure drop and hold-up of the flow in a pipe with different inclinations. Hasan and Kabir [13] investigated a model for approximating void fraction of two-phase flow through vertical and inclined annuli. Four flow regimes of bubbly, slug, churn and annular flow are identified in the study. Ghiaasiaan et al. [14] experimentally investigated the counter-current two-phase flow in vertical and inclined channels. They explored the influences of liquid properties on void fraction and two-phase flow patterns. Barnea et al. [15] accomplished two-phase flow experiments in inclined

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tubes. It is concluded that bubbly and churn flow are formed for the inclination higher than 50° and 70° , respectively. Oddie et al. [16] carried out two-phase examinations on an inclined pipe. They investigated flow pattern map for various inclination angles. Wongwises and Pipathattakul [17] investigated void fraction, pressure drop and flow patterns of two-phase flow in a narrow annular channel with horizontal and inclined orientation. The plug, slug, annular, bubbly-plug, bubbly-slug, churn, and distributed bubbly flow patterns were perceived in the research. The results demonstrated that the inclination angle affect greatly on the transition of the flow pattern, void fraction and pressure drop. Ali et al. [18] examined two-phase flow in a capillary channel between two plates with various directions consisting horizontal, vertically downward and upward and inclined. They evaluated the flow pattern and average and local void fraction for all direction. Bhagwat and Ghajar [19, 20] experimentally studied the gas-liquid two-phase flow in upward and downward inclined pipes. The results display a great influence of the pipe inclination on two-phase flow structure and the two-phase flow variables at small amounts of gas and liquid flow-rates. Kim et al. [21] studied the flow regimes of two-phase flow through a downward rectangular channel. The results show some different flow patterns such as falling film flow pattern and large-bubbly flow which identified in the low liquid superficial velocity wherever buoyancy force has a great influence. Resemblance and differences between vertically downward and upward churn flow are perused by Bouyahiaoui et al. [22]. It is concluded that the structure velocity through vertical downward flow is greater than vertical upward flow.

Compared with vertical and horizontal two-phase flow, a little data is accessible about two-phase flow in inclined channel. To investigate the present extent of knowledge, the significant purpose of this study is experimentally examine the influence of upward channel inclination (horizontal to vertical) on two-phase flow. To achieve this purpose, examinations of concentrated on flow visualization in gas-liquid two-phase flow were performed in 30 m channel utilizing air and water as fluid for the two phase flow system.

2. EXPERIMENTAL APPARATUS

The experimental setup displayed in Figure 1 is utilized for two-phase flow system that contains two horizontal sections and variable vertical sections. The test section made of transparent Plexiglas plates is utilized for flow visualization. The air supplied by compressor first moved through an air filter and pressure regulator. An air cooling system was utilized to decrease the high pressure and temperature of the compressed air. Next, the air is

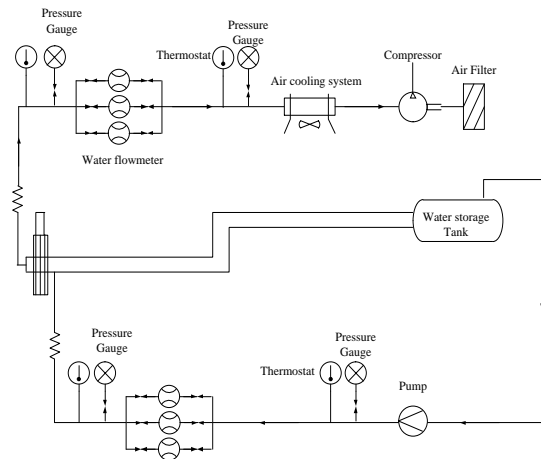


Figure 1. Deposition efficiency on a single square in channel

transported to gas mass flow-meters where the mass flow rate of air is adjusted accurately. The compressed air is then transmitted through a mixer to enter the test section. The liquid phase contains pure water supplied in a water tank is circulated in the setup utilizing a centrifugal pump. The pure water is then moved through a mass flow-meter where the flow-rate of the liquid phase is controlled. Afterwards, the water is permitted to mix with air at T-type mixer. The gas and liquid volumetric flow-rates were modified in an area of 2 to 10 m^3/h and 34 to 235 m^3/h , respectively. The system pressure is at atmospheric pressure and the system temperature is maintained at 25°C . The uncertainty related to measurements of mass flow-rates of air and water is approximated to be between $\pm 4\%$ and $\pm 10\%$, respectively. The thermocouples were utilized to evaluate temperatures at some positions in the experimental setup and the pressure gauges are used to measure pressure at some locations of the setup. The uncertainty of temperature measurements is $\pm 1^\circ\text{C}$.

Experiments were performed at several gas and liquid mass flow-rates, different vertical lengths of the channel. The bend of 90° was joined to the horizontal and vertical sections utilizing flanges. The bend is made of laser cutting Plexi-glass plates. Different length of channels including 50, 100 and 150 cm were utilized in the vertical section of the experimental setup to survey the effect of vertical section on the flow patterns.

3. RESULTS AND DISCUSSIONS

This section exhibits the result of flow visualization of two-phase flow in an inclined rectangular channel with 90° bend for various vertical lengths. The various flow patterns were created by systematically modified volumetric flow-rates of gas and liquid in the range of 2 to 10 m^3/h and 34 to 235 m^3/h , respectively. Based on the

observations, slug, churn and annular-mist flow are the significant flow regimes perceived in the vertical section of the channel. The physical appearance of these flow regimes in vertical section is demonstrated in Figures 2-4.

Flow pattern maps are depicted for different cases with the superficial air velocity varying between 1 and 20 m/s and superficial water velocity varying between 0.08 and 0.6 m/s . Three distinguished flow regimes are seen in vertical section concluding slug, churn and annular-mist flow regimes described as follows:

- Slug flow

An alternative mass of liquid comes into the vertical section and at the time the major mass of the liquid proceed the middle section, a little part of liquid comes downward. Also, another liquid mass goes upward and when these counter-current flows contact each other, some vortices are formed on the interface of the two phases of air and water. As a result, the liquid hold-up gets larger and consequently the gas phase appears as bubbles with a bullet shape in the liquid phase. The velocity of liquid phase is reduced due to this contrary flow.

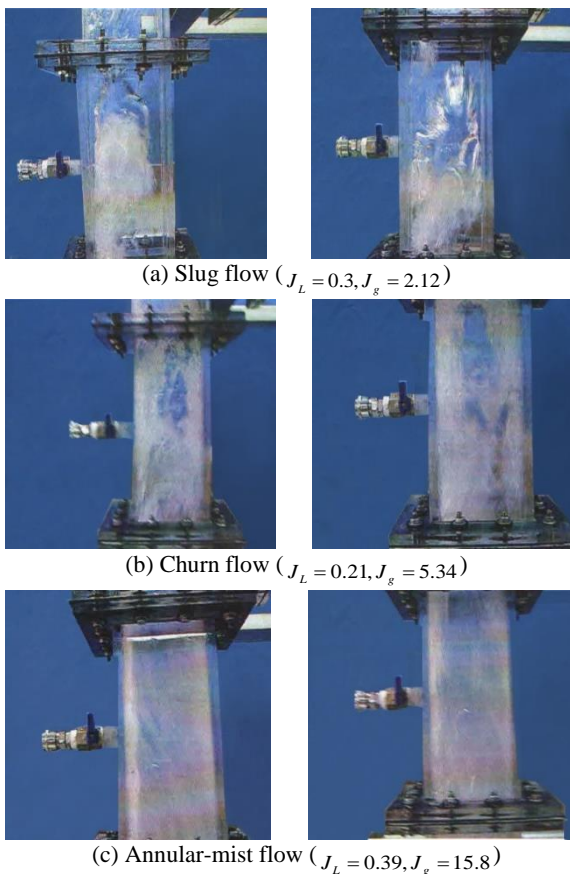


Figure 2. Flow regimes in horizontal-vertical-horizontal rectangular channel with vertical length of 0.5 m (a) Slug flow, (b) Churn flow, and (c) Annular-mist flow

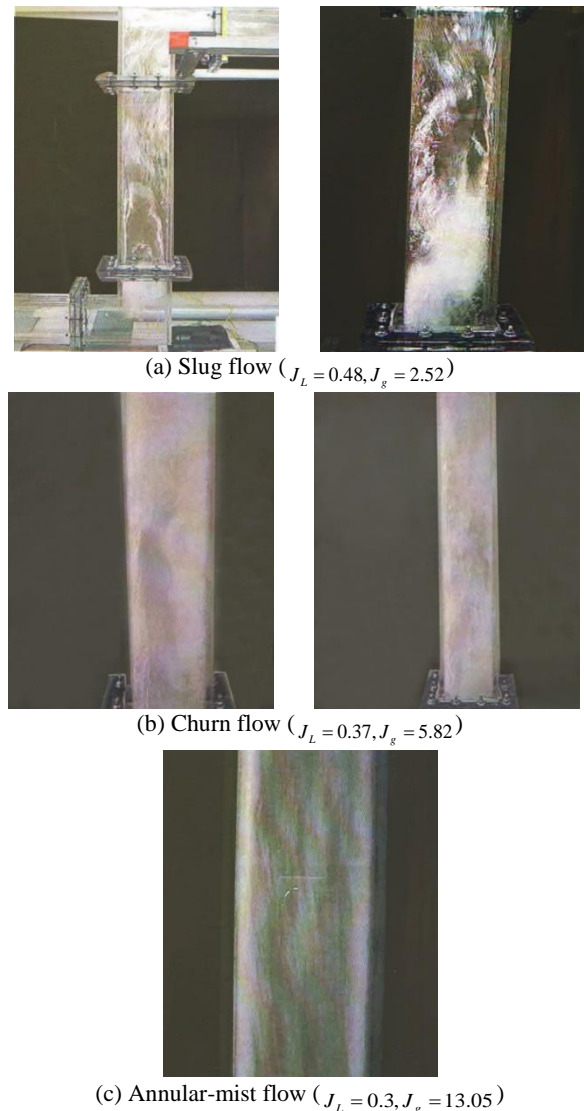


Figure 3. Flow regimes in horizontal-vertical-horizontal rectangular channel with vertical length of 1 m (a) Slug flow, (b) Churn flow, and (c) Annular-mist flow

- Churn flow

This pattern treat like the slug pattern, but the characteristic of disturbance and turbulence is distinct from that of slug flow. At greater liquid and gas superficial velocities, the flow became disordered and frothy. Churn flow is appeared by a failure of the slug flow bubbles. This causes an oscillatory movement, like the liquid down-ward and up-ward flow in the vertical section.

- Annular-mist flow

As mentioned in the previous studies, the main characteristic of annular flow is the conjunction of gas phase along the channel length. Also, the liquid phase reveals as an oscillating liquid film on the channel wall. With a greater increment in the gas flow-rate, the liquid

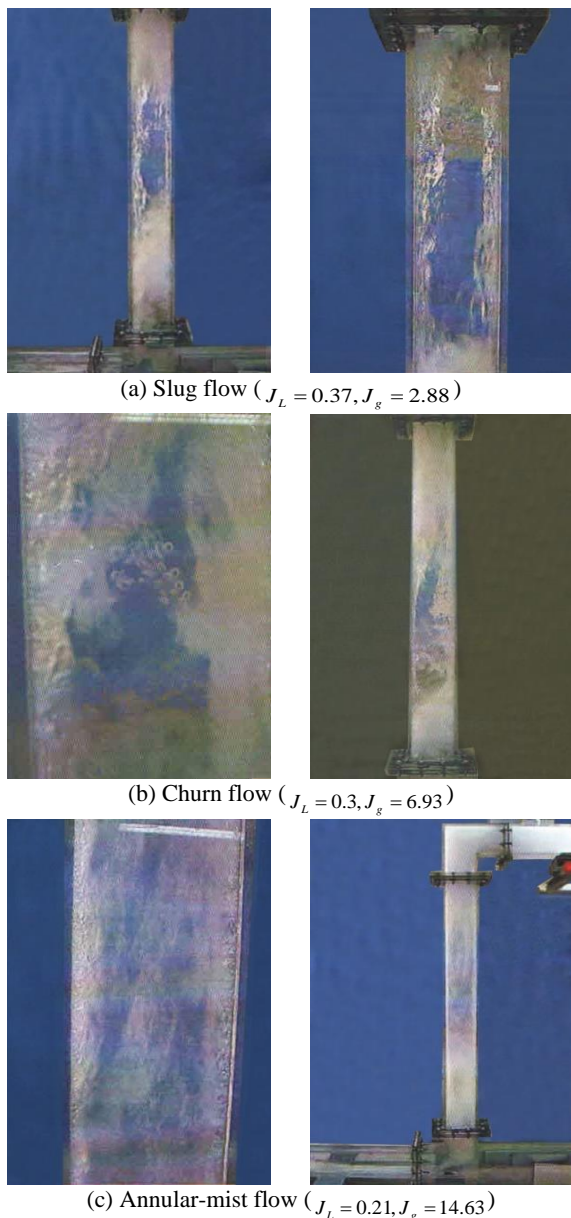


Figure 4. Flow regimes in horizontal-vertical-horizontal rectangular channel with vertical length of 1.50 m (a) Slug flow, (b) Churn flow, and (c) Annular-mist flow

slug is broke down and a consecutive gas core is created. In an annular-mist flow, the liquid current is not enough to sustain bridging liquid slug. A considerable volume of air bubbles is distributed in water which is now moving as layers nearby the walls. The water layer surface shows a great size of wavy flow. With a greater increment of the gas flow-rate, this wave size was observed to be withdrawing.

The observed flow regimes for the vertical length of 0.5 m are shown in Figure 2. Three different flow regimes, namely slug flow, churn flow and annular-mist flow are observed. Compared with the previous

researches for inclined and vertical pipe, bubbly flow was not seen for the present study at lower liquid and gas flow-rates. The reason is that air and water go into the vertical part of channel in a distinguished pattern at upstream of the channel. It causes the liquid phase obstructed air flow in the inclined bend and the gas flow is fastened, totally. Enhancing the mass flow-rate of the gas phase causes the pressure of air increased and the slug flow is formed instead of bubbly flow. At small amount of liquid mass flow-rate, pressure drop according to the vertical line is more than two-phase momentum, so water condensed at 90° bend and therefore the significant flow pattern at low liquid flow-rate is slug flow. With enhancing gas flow-rate, the formed bubble in the slug flow is disfigured and the flow regime disorganized and therefore the churn flow is formed. For higher gas flow-rat, gas shear force conducted liquid phase into the walls of the channel, thus the annular flow is formed.

Further pictures taken at close range by high speed camera for the vertical length of 1 m are presented in Figure 3. In this case, by increasing the vertical length, the size of Taylor bubbles is enhanced. As the length of the vertical section increased, the gravity force dominates the kinetic energy of the two-phase mixture, thus the droplets of liquid phase return into the Taylor-bubbles. Thus, the interface of two-phase became disordered. The closer it got to the end of the middle section, the more deformation caused for the Taylor bubble.

Figure 4 shows two-phase flow regimes for e rectangular channel with vertical length of 1.5 m. It can be seen that the area of the churn flow extended for higher vertical section. According to that the transition from the churn flow and annular-mist occurred gradually, the distinctive characteristic between these two flows is forward and backward flow in the churn flow pattern. Thus, for the vertical length of 150 cm, by increasing the riser length, the observed flow became more distorted, frothy and bubbly. It can be concluded that the outstanding flow regime in the present examination is churn flow. The main influence of enhancing the vertical length is greater back-ward flow. Enlarging the vertical section causes the momentum of liquid to disintegrate due to the effect of gravitational force and greater pressure drop.

Flow visualizations at various vertical lengths display that the flow pattern structures are not greatly varied by changing the vertical length. The change in upward middle section has an influence on the transition boundaries between various flow patterns. The flow pattern maps with transition boundaries between various flow patterns for different vertical lengths are exhibited in Figures 5-7.

These flow pattern maps are introduced by utilizing gas and liquid superficial velocities (U_{sg} and U_{sl}) as frame of references. As a result, these flow pattern maps are introduced to be utilized for affiliating the evaluated

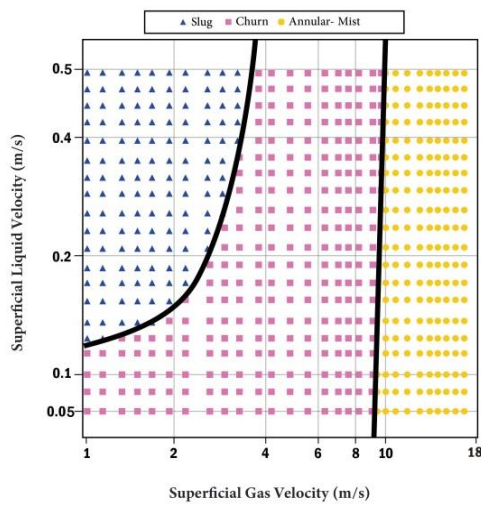


Figure 5. The flow pattern map for the vertical length of 0.5m

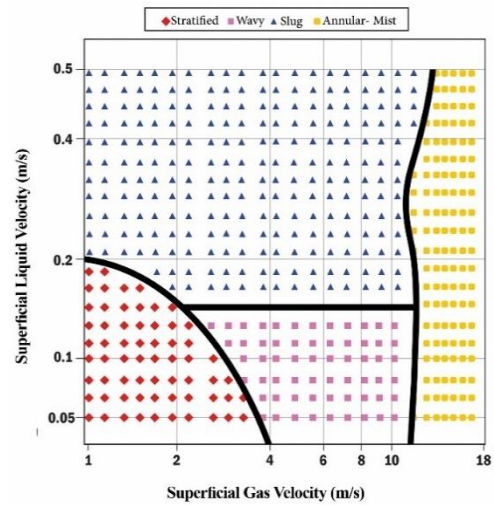


Figure 8. The flow pattern map in the fully developed section of horizontal line

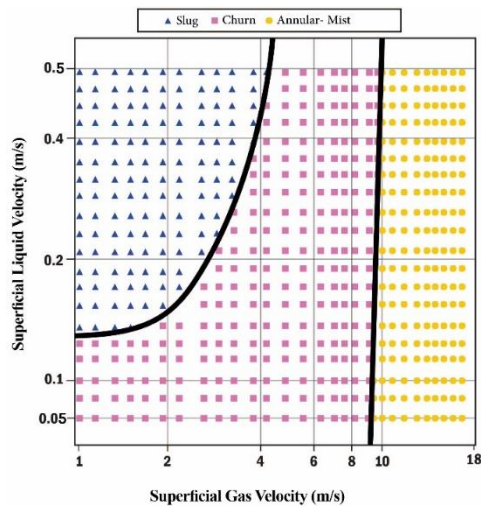


Figure 6. The flow pattern map for the vertical length of 1m

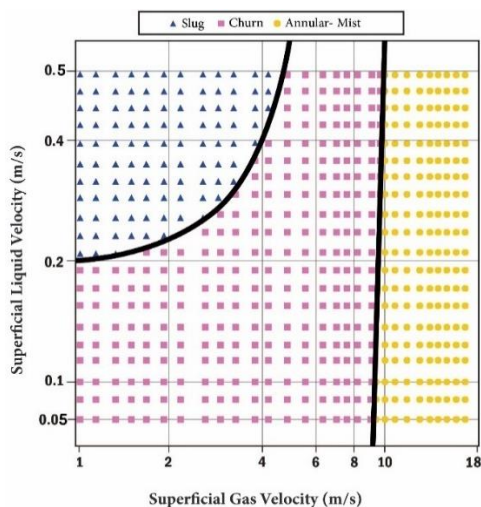


Figure 7. The flow pattern map for the vertical length of 1.5m

data in this study with corresponding flow patterns. The liquid and gas superficial velocity is acquired from the mass flow-rates using Equations. (1) and (2).

$$U_{sl} = \frac{Q_l}{A} \tag{1}$$

$$U_{sg} = \frac{Q_g}{A} \tag{2}$$

where Q_l and Q_g are the volumetric flow-rates of liquid and gas phase, respectively and A is the area of the cross section of the channel.

The two-phase flow regimes through horizontal line of channel are under the effect of disturbance persuaded by vertical section and mixer. The vertical length between two horizontal lines influences the upstream flow regimes, greatly. The considerable influence of back-ward flow of vertical part on the horizontal line is greater hold-up of water. Increasing the vertical interval between the horizontal lines creates greater momentum loss across the channel. Also, it is observed that enhancing the height between entry and exit parts leads the beginning of annular flow to greater air superficial velocities. This happening is because of that increasing the liquid amount at 90° bend inlet part needs greater gas shear force for passing to annular flow regime.

The flow regimes in the present study are characterized by gas shear force and gravity force. The gravity force results in forming of vortexes and back-ward flow. This event is connected to the length of vertical part of the test section. The dimensionless parameter linked to the present study is Froude number. The Froude number is the ratio of the flow inertia to the external field (the gravity force). This dimensionless number is determined as follow:

$$Fr = \sqrt{\frac{\rho_G}{\rho_L - \rho_G}} \frac{U_G}{\sqrt{D_h g}} \quad (3)$$

The variation of Froude number for the transitions of available flow patterns are explained according to the dimensionless vertical length in Table 1. The transition between slug and churn flow happens whereas the mass flow-rate of gas phase was enhanced and, accordingly, the liquid phase did not amass at 90° bend inlet. It can be observed that by increasing vertical length of channel, the Froude number became greater. It is due to that the liquid hold-up in 90° bend inlet is higher, therefore slug became greater. The transition to the annular-mist flow pattern takes place when the gas shear force is increased. Increasing the vertical section does not affect the gas shear force, greatly. So, the influence of various middle sections on this transition is not distinguished by vertical lengths.

Two-phase flow regimes through inlet and outlet horizontal sections of the channel are affected by disturbances caused by inclined section. For both horizontal lines, the flow patterns are categorized into two parts: fully developed part and inclined section. The flow pattern map in the fully developed section is shown in Figure 8 which contains stratified, wavy, slug and annular flow. The result of this figure is in a great agreement with the result of the study of Mandhane et al. [23] for horizontal pipes. The flow treatment at inclined

inlet section is specified by gas-liquid interaction among the inlet and inclined section. Three flow regimes of wavy, slug and annular were seen at 90° bend inlet section as shown in Table 2. As seen, the prominent flow pattern is slug flow. The significant effect of backward flow of vertical section on the 90° bend inlet part is larger hold-up of water. When the flow moves along the vertical section, the hold-up of water flourish slowly and this treatment resulted the slug flow creation. By enhancing the vertical length between the inlet and outlet horizontal sections, the greater upstream flow regimes are affected. It can also be observed that, enhancing the vertical section shifts the beginning of annular flow to greater gas superficial velocities. This behavior can also be illustrated by increased liquid level at inlet bend section which needs greater gas shear force for transition to annular flow pattern.

TABLE 1. Froude number variation for various middle lengths

Length of middle section, cm	Froude number variations	
	Slug to churn flow	Churn to annular-mist flow
50	0.041-0.170	0.401-0.446
100	0.041-0.191	0.408-0.457
150	0.041-0.213	0.419-0.462

TABLE 2. Two-phase flow regimes types according to the gas and liquid superficial velocities at the inclined inlet section of the channel

	H=50 cm		H=100 cm		H=150cm	
	U_{sL} (m/s)	U_{sG} (m/s)	U_{sL} (m/s)	U_{sG} (m/s)	U_{sL} (m/s)	U_{sG} (m/s)
Slug flow	0.11-0.5	0.6-3.8	0.14-0.5	0.6-4.5	0.2-0.5	0.6-5
Churn flow	0.05-0.5	0.6-9	0.05-0.5	0.6-9	0.05-0.5	0.5-9.5
Annular-mist flow	0.05-0.5	9-18	0.05-0.5	9-18	0.05-0.5	9.5-18
Transition line of slug to churn	0.11-0.5	0.6-3.8	0.14-0.5	0.6-4.5	0.2-0.5	0.6-5
Transition line of churn to annular-mist flow	0.05-0.5	Constant value of 9	0.05-0.5	Constant value of 9	0.05-0.5	Constant value of 9.5

4. CONCLUSION

In the present study, two-phase flow experiments for the rectangular channel with 90° bends have been accomplished and flow pattern maps for vertical section have been depicted according to the measured data. A high speed video camera was utilized to evaluate flows. Three various flow patterns, namely slug flow, churn flow and annular flow were recognized for the middle vertical section.

The following conclusions are resulted from the present work:

- The prominent flow regime in the vertical section is churn flow regime. Two other flow regimes namely slug and annular-mist flow regime are also identified.
- The transition between slug and churn flow happens whereas the mass flow-rate of gas phase was enhanced.
- The flow pattern structures are not greatly varied by changing the vertical length.
- Increasing the vertical length leads the beginning of annular flow to greater air superficial velocities.

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Persian Abstract

چکیده

در این مقاله به منظور تحلیل رفتار جریان دو فازی در یک کانال مستطیلی شیبدار با زاویه ۹۰ درجه برای طول‌های مختلف عمودی، یک بررسی آزمایشگاهی انجام شده است. بخش اصلی آزمایش (با طول ۳۰ متر) شامل دو بخش افقی و یک بخش عمودی میانی است. سه طول عمودی ۵۰، ۱۰۰ و ۱۵۰ سانتی‌متری در طول بخش آزمایش استفاده شده است. سطح مقطع کانال مستطیلی ۱۰ سانتی‌متر × ۱۵ سانتی‌متر می‌باشد. سیال‌های مورد استفاده در این تحقیق هوا و آب بوده است. الگوهای جریان مختلفی با تغییر دبی حجمی گاز و مایع به ترتیب در محدوده ۲ تا ۱۰ و ۳۴ تا ۲۳۵ m^3/h ایجاد می‌شود. سیستم ویدئویی با سرعت بالا برای دستیابی به دنباله تصویر جریان تحت شرایط مختلف مورد استفاده قرار گرفت. اثرات طول عمودی بر رژیم‌های جریان و مرزهای انتقال الگو مورد بررسی قرار گرفته است. با توجه به تجسم جریان، هیچ گردابی در بخش عمودی مشاهده نگردید. نتایج نشان داد که رژیم جریان در بخش عمودی بصورت ریزشی است. در نهایت می‌توان دریافت که ساختارهای الگوی جریان تحت تأثیر تغییر طول عمودی قرار نمی‌گیرند.