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TWO-PHASE FLOW PATTERNS DURING AIR-WATER UPWARD FLOW ACROSS TUBE BUNDLE

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Abstract. *This paper presents flow pattern experimental results for upward flow of air-water mixtures across a triangular tube bundle with 19 mm OD tubes and 24 mm transversal pitch. Experimental conditions covered water superficial velocities ranging between 0.020 and 1.500 m/s, and air superficial velocities between 0.20 and 10.00 m/s. Flow patterns were identified subjectively, based on visual observations through side windows, helped by images and videos captured with a digital camera, and objectively based on the analyses of the signal of a differential pressure transducer, adopting the k-means clustering method. Experimental results are compared with predictive methods available in the literature.*

Keywords: *Two-phase flow; tube bundle; flow pattern; objective method; k-means.*

1 INTRODUCTION

According to Noghrehkar *et al.* (1999) and Green and Hetsroni (1995), it is estimated that more than half of the shell and tube heat exchangers in industry operate under two-phase flow conditions in the shell side, nonetheless the number of research and publications focused on the external two-phase flow in considerably reduced in comparison to intube flow.

Heat exchanger designers need reliable predictive methods for heat transfer coefficient, pressure drop and void fraction for the thermo-hydraulic analysis of the equipment. The heat transfer coefficient is related to the equipment thermal capacity, the pressure drop is related to the required pumping power to propel the flow through the equipment, and the void fraction affects the refrigerant inventory, pressure drop and heat transfer coefficient. In the case of refrigeration industry, the correct estimative of fluid inventory is a key factor for the analysis of economic viability, since the refrigerant cost represents a significant parcel of the system total cost.

Most of the refrigerant mass in thermal systems is usually in the heat exchangers. In a recent survey, Ribatski (2009) showed that the leakages in heat exchangers are inevitable, and also that they are related to the refrigerant inventory in these devices. Consequently the development of more reliable and precise predictive methods would allow the design of more compact heat exchangers, based on the reduction of safety factors adopted by designers.

Another important aspect concerning external cross flow in tube bundle is the flow induced vibrations (FIV), which as shown by Kanizawa *et al.* (2012), Green and Hetsroni (1995), Pettigrew and Taylor (2003 a,b) and Klein *et al.* (2014) can imply in equipment life cycle reduction due to fretting wear or fatigue, or in worse cases FIVs can cause equipment collapse within few working hours, for conditions of FIV induced by fluid-elastic instabilities. In this context, Green and Hetsroni (1995), Pettigrew and Taylor (2003a,b, 2004) and Khushnood *et al.* (2004) indicate that non-continuum flow patterns should be avoided because they amplify heat exchangers vibration problems. Therefore reliable and generalized flow pattern predictive methods that can be used as design tool are required for a better heat exchanger design, to reduce or even avoid critical operational conditions.

Flow pattern maps are used for the prediction of local flow pattern during internal and external flow, and in the case of external flow across tube bundles the number of predictive methods available in the open literature is considerably reduced.

As far as the present authors know, Grant and Chisholm (1979) were the first to propose a flow pattern for upward flow across horizontal tubes, which consist of a flow chart with the axis given by phases superficial velocities multiplied by factors that are function of fluids properties. These authors have performed experiments in a baffled heat exchanger model, for air-water mixtures flow across a triangular tube bundle.

Using the same transitions criteria presented by Grant and Chisholm (1979), Pettigrew *et al.* (1989) proposed an alternative flow pattern map, differing from the previous one by adopting non-dimensional parameters for the coordinate axis. These authors have also extended the bubble and intermittent transition line, to cover their experimental database.

Later on, Ulbrich and Mewes (1994) proposed a new flow pattern map based on a broader database that comprises experimental results obtained by the authors, and results gathered in the open literature.

More recently, Xu *et al.* (1998) proposed a flow pattern map based on their experimental results for air-water two-phase crossflow in a baffled heat exchanger model with square tube bundle. Additionally to the previous methodologies that described and predicted only the bubbly, intermittent and annular flow patterns, Xu *et al.* (1998) have observed and defined a transition criteria between intermittent and churn flow pattern.

Figure 1 presents the transition curves according to the abovementioned methods. This figure shows that despite the fact the methods agree among them in transition lines trends, they present a great difference in absolute values of the transitions velocities. In Fig. 1, the transition lines given by Grant and Chisholm (1979) were extrapolated in order to cover the total range of superficial velocities given in the plot. The method proposed by Pettigrew *et al.* (1989) was not presented due to the fact that it is similar to the Grant and Chisholm (1979) method differing only by the extension of the transition line between intermittent and bubbly flow.

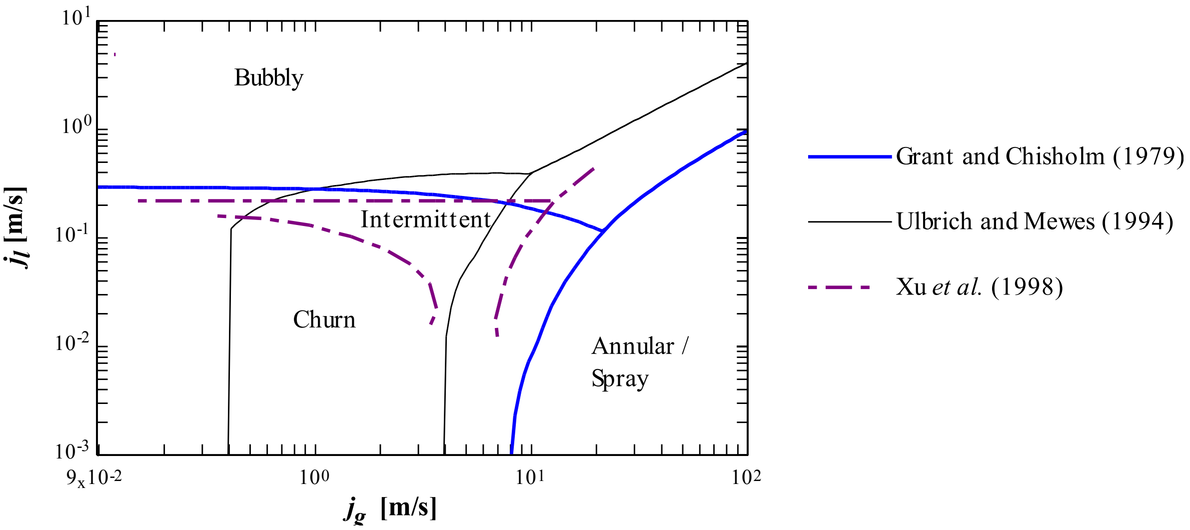


Figure 1. Predictive methods for flow patterns.

Ulbrich and Mewes (1994) flow pattern map presents the transition between bubbly and intermittent flow pattern for reduced liquid velocity, not predicted by Grant and Chisholm (1979) and Xu *et al.* (1998) methods. This difference is due to the fact that Ulbrich and Mewes (1994) included experimental results presented by Kondo and Nakajima(1980), which comprises experiments for reduced liquid velocities. The occurrence of bubbly flow pattern for this condition is due to the reduced air injection rate.

Based on the discussion above presented, it can be concluded that there is no generalized flow pattern predictive method, indicating that each method is appropriate only for operational conditions and geometrical configurations similar to the database adopted for its development. Consequently this study aims to contribute to the knowledge about external two-phase flow across tube bundle. The paper presents experimental flow pattern results obtained during upward flow of air-water mixtures across a triangular tube bundle. Experimental results are compared with predictive methods available in the open literature.

2 EXPERIMENTAL FACILITY AND PROCEDURE

Figure 2 depicts the schematics of the experimental facility designed and built at EESC-USP to study two-phase flows across tube bundles. Figure 3 shows a picture of the experimental bench.

The test facility is composed by water and compressed air loops, measurement system and the test section.

The water loop shown in Fig. 2 consists of a reservoir, an 11.4 kW centrifugal pump controlled by a variable frequency drive and electromagnetic volumetric flow meters. The electromagnetic flow meters presents uncertainty of 0.5% of the measured value, and maximum flow rates of 6.4 and 56 m^3/h for the transducer of ½ and 2 inches, respectively (0.00178 and 0.01560 m^3/s).

Just downstream the flow measurement devices, a heat exchanger was installed to control the water temperature. It consists of a shell and tube heat exchanger, and operates with water cooled by an evaporative cooling tower, not shown in Fig. 2. This heat exchanger is used to avoid significant water temperature changes during the experiments.

The air is compressed by a 40 HP rotary screw compressor, with operating gauge pressure of 7.5 bars and maximum flow rate of 4672 Nl/min (0.0779 Nm^3/s). Just downstream the compressor, an aftercooler was installed to cool down the air and to favor the air moisture condensation in the reservoir, which counts with a liquid trap in the bottom region. The aftercooler operates with water from the evaporative cooling tower. These devices are not shown in Fig. 2.

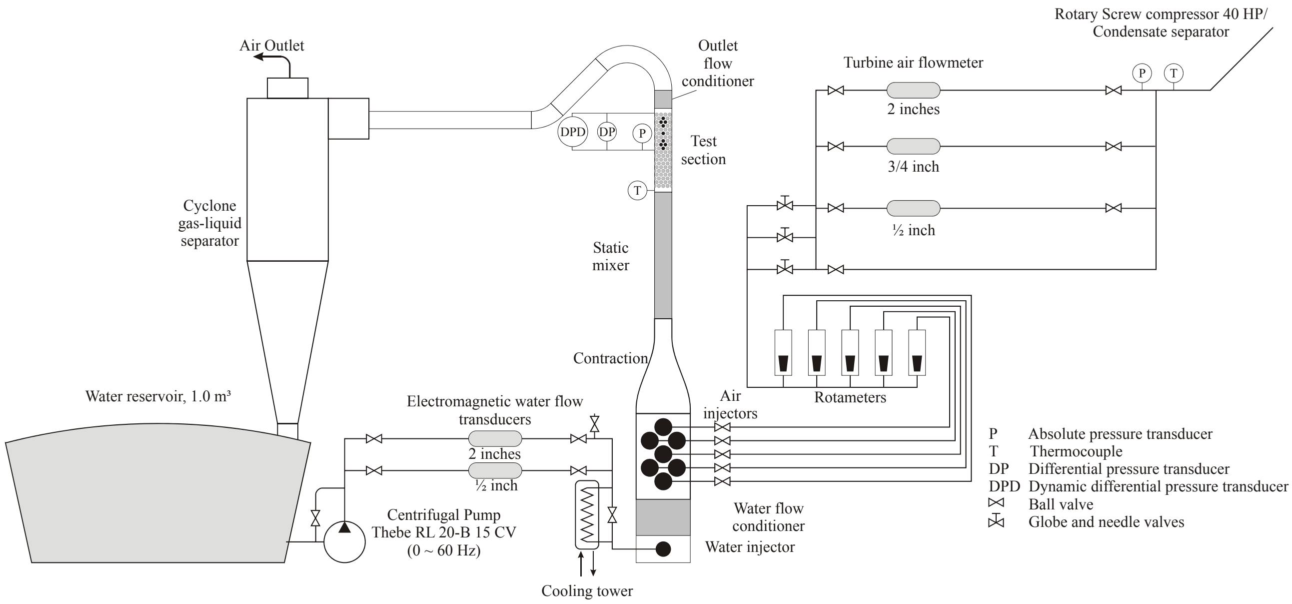


Figure 2. Schematics of experimental facility.

Figure 3. Experimental facility designed and built at EESC-USP for the experimental campaign.

A pressure regulating valve was installed downstream the reservoir to control the air pressure in the flow measuring section, corresponding to the turbine flowmeters in Fig. 2. With a constant pressure upstream the needles and globe valve, it is possible to perform a manual control of the flow rate, without an automated closed loop control system.

Air flow rate was measured with three turbine flow meters, presenting maximum ranges of 8.5, 85 and 340 m^3/h for the ½, 1 and 2 inches transducers, respectively (0.002, 0.023 and 0.094 m^3/s), with measurement uncertainty lower than 1% of the measured value. Close to the transducers, a PT100 and an absolute pressure transducer were installed to determine air thermodynamic state, allowing the determination of air density and therefore the air mass flow rate. In order of covering a broad range of superficial velocities, different flow meter were set according to the experimental condition given by the air and water superficial velocity.

The heat exchangers for the air and water temperature control were used to minimize effects of air contraction and expansion along the test section due to thermal non-equilibrium. Air flow rate was controlled manually through the use of two needle and one globe valves.

Just downstream the controlling valves, five rotameters were installed to check the air flow distribution among the air injectors, to avoid damaging of the injectors due to excessive flow.

From the bottom to the top region of Fig. 2, the test section setup consists of water injection and conditioning section, air injection section, contraction, static mixer, the tube bundle and outlet flow conditioner. Downstream the test section outlet, the flow is directed to the gas-liquid cyclone separator, and then water is received in a reservoir, and air is driven to the laboratory outside.

Water is injected with a perforated tube, and conditioned with honeycomb flow straightener. Air is injected through seven membrane air injectors distributed according to five horizontal rows. The maximum flow rate of each injector is 816 Nl/min. The static mixer was built and installed to distribute the phases uniformly along the cross section, in order of mimicking flow distribution in the core of a large scale industrial shell and tube heat exchanger.

The bundle consists of a triangular tube bundle (staggered with 30°), counting with 19 mm OD tubes distributed according to 20 horizontal rows and 4 vertical columns. In the side walls of the bundle, half tubes were installed to avoid preferable bypass flow, as recommended by Chisholm (1984). The transverse pitch is equal to 24 mm, resulting in a transverse pitch per diameter ratio equal to 1.26.

Pressure taps were installed after the seventh and eighteenth rows, and the pressure drop is measured with three Endress Hauser PMD75 differential pressure transducers, ranging from -3 to 3 kPa, -3 to10 kPa and -3 to 300 kPa, and with uncertainty of 0.075 % of the set span. Additionally, a Validyne fast response differential pressure transducer, model DP15 with demodulator CD23 and diaphragms 030 and 038 (up to 8.6 and 55 kPa, respectively) is installed, for the measurement of the time varying signal of pressure drop.

A National Instruments acquisition system installed in a desktop computer was employed for the signal measurement and for the pump control. The acquisition program was implemented in LabView 8.2.

The text section contains two side windows to allow visual identification of the flow pattern, and a Nikon digital camera model D5100 was used to capture pictures and record videos of flow patterns during experiments, and to help the flow patterns identification.

2.1 Experimental procedure

Previously to the beginning of the experiments, the cooling tower, the water pumps responsible for feeding the heat exchangers and the compressor are turned on. Then, all the transducers are checked in order to identify possible incoherencies.

After this initial procedure, the electromagnetic flow meter is selected based on its measurement range. Then, the water pump is turned on, and its superficial velocity is adjusted through a closed loop PI (proportional and integral) controller implemented in LabView and actuating through the data acquisition system.

Simultaneously to the adjustment of the liquid flow rate, a turbine flow meter is selected based on the desired air flow rate, and the air superficial velocity is adjusted by manipulating needle and globe valves.

Once the air and water superficial velocities are set, unsteadiness of the system based on pressure drop and flow rate variations are checked. Then, the data log is started and the signals are acquired for at least one minute. During the acquisition time, a picture of the flow was captured and a movie was recorded with the use of the digital camera.

After acquiring the experimental data, the air flow rate is adjusted for a new condition characterized by a different air superficial velocity, and the procedure abovementioned is repeated and data for a new experimental condition is obtained.

Experimental conditions covered water superficial velocities between 0.020 and 1.500 m/s, and air superficial velocities between 0.20 and 10 m/s.

2.2 Data reduction

The superficial liquid and gas velocities, j_l and j_g respectively, are evaluated based on the minimum flow cross sectional area, corresponding to the minimum distance between the tubes of the same row. Reynolds number for single-phase flow is based on the tube external diameter and the superficial velocities.

Flow patterns were identified subjectively during the experiments, and after were verified with the help of the flow pictures and movies.

A grouping method was employed for the objective flow pattern identification, and for this study the *k-means* clustering method was implemented. According to MacQueen (1967), Sempertegui-Tapia (2011) and Sempertegui-Tapia *et al.* (2013), this method consists in successive centroids and groups determinations, in a way that the Euclidian distance between all points attributed to a group and the group centroid is smaller than the distance to the centroid of another group. The group centroid is calculated for each iteration based on the arithmetic mean of all points in the group. Convergence is obtained when no variation of centroids values is verified.

Six regions were defined for the grouping method to produce the same number of flow patterns identified subjectively. As indicated by Su and Dy (2004), the *k-means* clustering method can provide distinct data groups depending on the centroid initial guesses, and for this study it was analyzed the possibility of using guess centroids as random experimental data point among the entire database, and one experimental data point for each flow pattern identified visually. However, both approaches resulted in the same regions, or flow patterns.

For the execution of the grouping method, the following parameters were considered as metrics, all based on the fast response differential pressure transducer: arithmetic mean, standard deviation, peak-to-valley value and signal kurtosis.

2.3 Experimental facility validation

Initially, single-phase experiments were performed and their results were compared against predictive methods from literature in order of evaluate the pressure drop measurements.

Figures 4 and 5 show the experimental results for water and air single-phase flows, respectively. These figures also display comparisons against the single-phase pressure drop results and the predictive methods of ESDU (2007), Gaddis (2010) and Zukauskas and Ulinskas (1983). Based on both figures, it can be concluded that the experimental results and the predictions agree reasonably well. Zukauskas and Ulinskas (1983) method predicted 95 and 53% of experimental results for water and air flow within an error band of ±30%, respectively. ESDU (2007) predicted 72 and 37%, and Gaddis (2010) predicted 35 and 21% of experimental results for water and air, respectively.

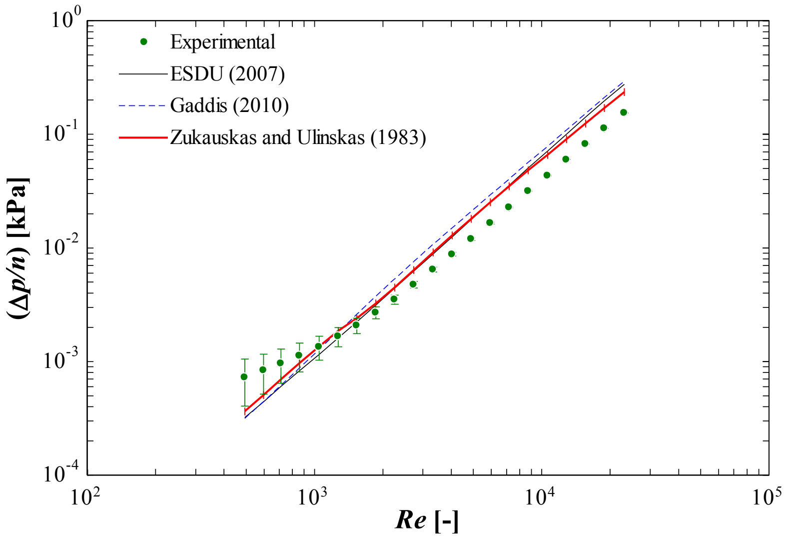


Figure 4. Experimental results for water single-phase flow, Kanizawa and Ribatski (2014).

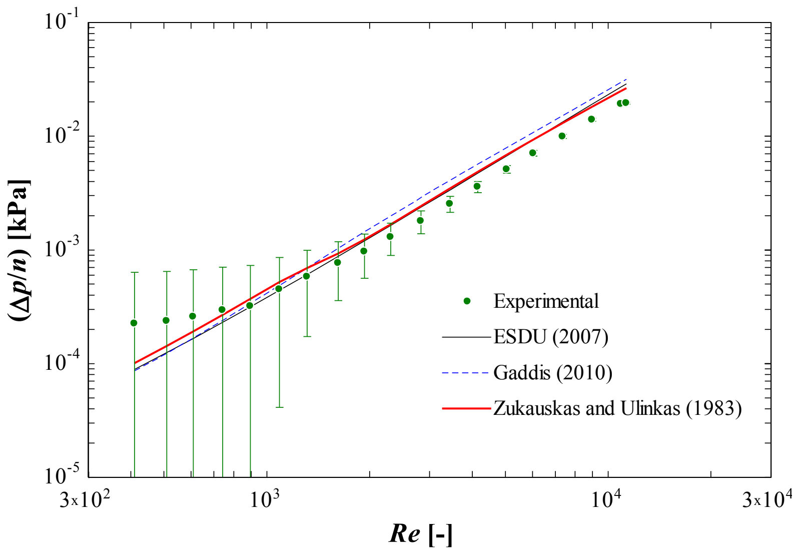


Figure 5. Experimental results for air single-phase flow, Kanizawa and Ribatski (2014).

It must be highlighted that the predictive methods for single-phase pressure drop across tube bundles presents deviation higher than 80% from each other depending on the Reynolds number, indicating that there is no consensus about predictive methods for external flow across tube bundle, even for single-phase condition.

3 RESULTS AND DISCUSSION

The following flow patterns were identified based on visual observations and Fig. 6 depicts images of each flow pattern:

- Bubbly flow: observed for reduced gas velocities. This flow pattern is characterized by the presence of small diameter gas bubbles dispersed in a continuum liquid phase. The bubbles are smaller than the spacing between parallel neighbor tubes;
- Large bubbles: observed for intermediary gas velocities, and reduced liquid velocities. By increasing the gas fraction, small bubbles coalesce and form larger bubbles. This flow pattern is characterized by the presence of large bubbles with characteristic dimensions larger than the space between parallel neighbor tubes, and downward movements of liquid phase were not observed;
- Churn flow: observed under conditions of intermediary gas and liquid velocities. With the increment of gas fraction, bubbles coalesce forming large portions of gas. This flow pattern is characterized by liquid slugs intermittently propelled by large gas bubbles. For this flow pattern, the effects of gravitational forces on the liquid phase are evident causing that liquid portions intermittently move to downward direction, and soon after the liquid slugs are propelled by the flow to the upward direction;
- Intermittent flow: observed for intermediary liquid velocity and intermediary to high gas velocity. By increasing the gas velocity, large portions of gas are formed, and the liquid slugs are intermittently propelled through the test section. Due to the elevate flow kinetic energy, gravitational effects are not evident for the liquid phase, since downward movements of liquid phase are not observed;
- Annular flow: observed for reduced liquid velocities, and for high gas velocities. Increasing the gas velocity, the flow becomes dominated by gas phase inertial effects. This flow pattern is characterized by continuum liquid film over tubes and section walls, with continuum gas flowing in the tube bundle core. Dispersed liquid droplets are observed in the gas core;
- Dispersed bubbles: verified for intermediary gas velocities, and for high liquid velocities. Due to the high kinetic energy of the liquid flow, eventual large bubbles are broken due to the elevated turbulence. This flow pattern is characterized by a high concentration of small diameter gas bubbles;

Figures 7 and 8 present the flow pattern maps identified subjectively and objectively, respectively. The transition curves according to Grant and Chisholm (1979), Ulbrich and Mewes (1994) and Xu *et al.* (1998) flow pattern maps are also presented in Fig. 7.

Table 1 presents the comparison between the flow patterns identified subjectively, and the predicted patterns according to the methods proposed by Grant and Chisholm (1979), Ulbrich and Mewes (1994) and Xu *et al.* (1998). Except for the comparison with Xu *et al.* (1998) method, churn flow pattern was considered as intermittent, and for all comparisons large and dispersed bubbles flow patterns were considered as bubbly flow. According to this table, it can be concluded that Ulbrich and Mewes (1994) flow pattern map is more appropriate for the prediction of the experimental results obtained, with 83.3 % of flow patterns predicted correctly. This can be attributed to the fact that this method predicts bubble flow pattern for reduced liquid velocities, not shown by the others predictive methods.

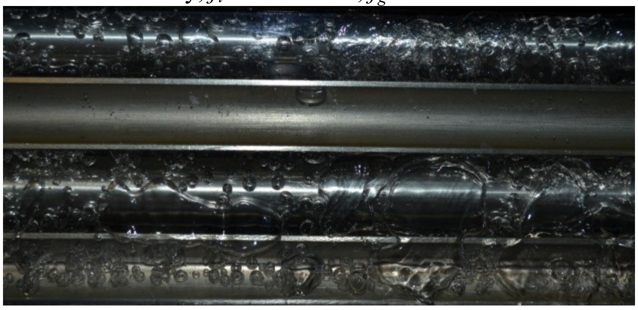
This table also presents comparison between the flow patterns identified objectively and the predictive methods. From a comparison between Figs. 7 and 8, it can be noticed that in general the flow pattern maps based on objective and subjective methods agree reasonably well, and the flow patterns identified based on both methods can be corresponded among each other according to the correspondence presented in Tab. 2. The objective method did not identify the large bubbles flow pattern, and this can be attributed to the fact that although gravitational effects was not evident for the liquid phase during large bubbles flow, gas bubbles were larger than the distance between the tubes, and therefore the flow topology is similar to the topology of bubble flow pattern. Consequently the large bubbles flow pattern can be considered as a transition between bubbly and churn flow patterns.

From Fig. 8 and Tab. 2, it can be also noticed that intermittent flow pattern was divided into regions D and F, the second one characteristic of intense harshness during liquid slug passage. This severity causes great amplitude in pressure drop fluctuations, implying in distinct pressure drop signal when compared to region D.

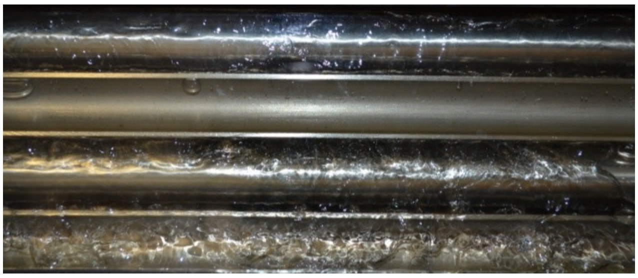
Based on Tab. 1 for the comparison between flow patterns identified objectively and predicted according to the flow pattern maps available in the open literature, it can be concluded that the Ulbrich and Mewes (1994) method also presents the best prediction of experimental results.


Bubbly, $j_l = 0.031$ m/s, $j_g = 0.27$ m/s


Large bubbles, $j_l = 0.054$ m/s, $j_g = 0.55$ m/s


Churn, $j_l = 0.054$ m/s, $j_g = 1.40$ m/s


Intermittent, $j_l = 0.060$ m/s, $j_g = 4.85$ m/s


Annular, $j_l = 0.022$ m/s, $j_g = 10.00$ m/s


Dispersed bubbles, $j_l = 1.343$ m/s, $j_g = 1.40$ m/s

Figure 6. Flow images for each flow pattern identified subjectively.

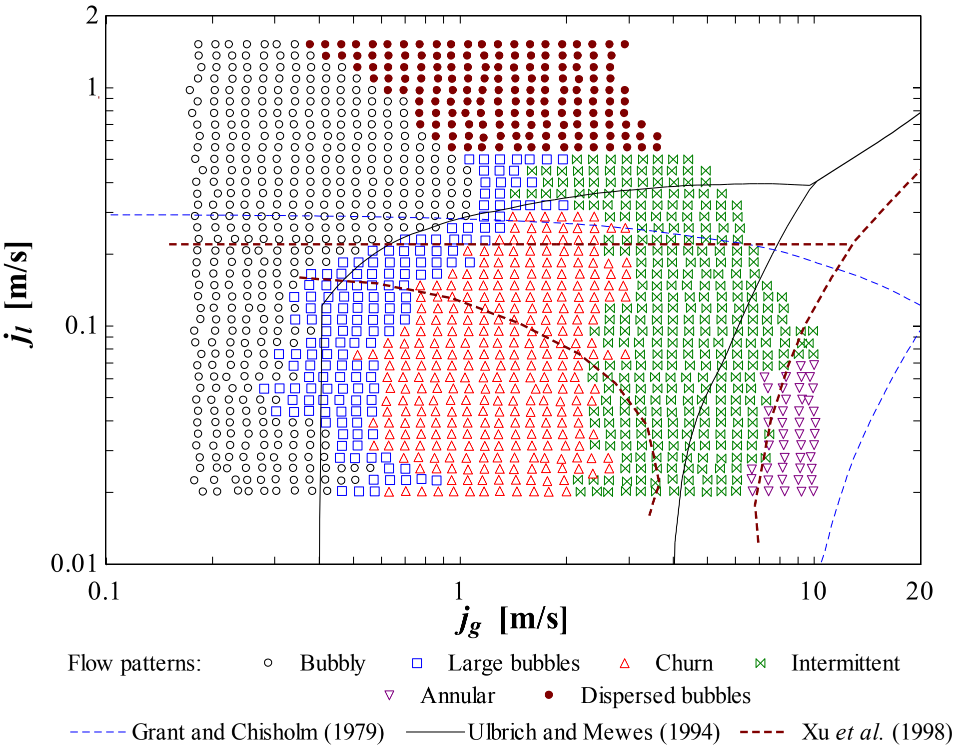


Figure 7. Flow patterns identified subjectively.

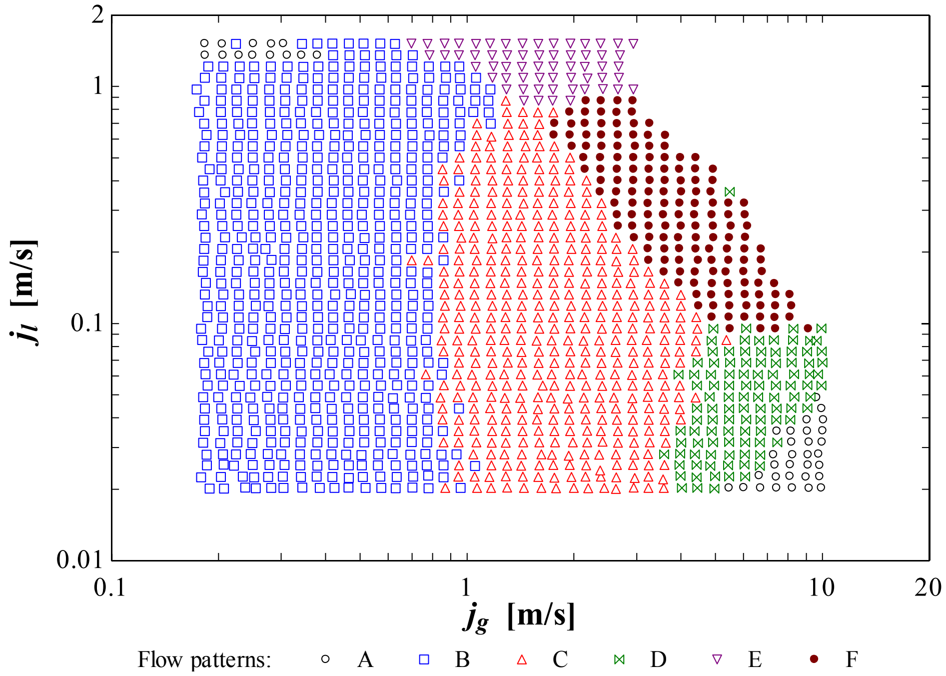


Figure 8. Flow patterns identified objectively.

Table 1. Parcel of experimental results correctly predicted by flow pattern predictive methods.

Experimental	Identified subjectively	Identified objectively
Grant and Chisholm (1979)	66.7	57.8
Ulbrich and Mewes (1994)	83.3	73.0
Xu *et al.* (1998)	62.9	49.1

Table 2. Correspondence of flow patterns identified objectively and subjectively.

Flow pattern identified objectively	Flow pattern identified subjectively
A	Annular
B	Bubbly
C	Churn
D	Intermittent
E	Dispersed bubbles
F	Intermittent

According to Tab. 1, all methods presented worse predictions for flow patterns identified objectively than identified subjectively. This can be attributed to the fact that all flow pattern maps were developed based on experimental results for flow patterns identified subjectively, through side windows. Noghrehkar *et al.* (1999) presented an experimental study on flow pattern objective identification, using a resistive probe installed in the core of a heat exchanger model. Adopting procedure similar to the method presented by Jones Jr. and Zuber (1975), Noghrehkar *et al.* (1999) were able to identify flow patterns in the core distinct from the flow patterns identified subjectively by visual observations, indicating that the flow close to the heat exchanger wall can be different from the flow in the bundle core. Additionally, the flow patterns identification based on visual observations depends on the observer judgment, and consequently different research groups can point out different flow patterns for the same experimental condition.

Based on this discussion, it can be concluded that flow pattern predictive methods should be developed based on objective characterizations.

4 CONCLUDING REMARKS

This study addressed experimental results for flow patterns during upward flow of air-water mixtures across triangular tube bundles. The following conclusions can be drawn:

- The number of flow pattern predictive methods during two-phase cross flow in tube bundle is significantly reduced. Despite the fact that all methods evaluated present similar transition curves trends, the flow velocities corresponding to the transitions present significant difference in absolute values among each other. Therefore, it can be concluded that there is no generalized flow pattern predictive method for external flow condition;
- New flow pattern experimental results were presented. Flow patterns were identified subjectively, by visual observations helped by images and videos recorded during the experiments, and objectively, with the use of *k-means* clustering method. Most of the transitions were similar according to both methods; however the objective method was not capable of identifying large bubble flow pattern. This can be attributed to the fact that the metrics adopted for the method execution do not differ much from bubble flow pattern to large bubbles, and to the fact that the flow topology is similar for both patterns. Considering pressure drop and flow induced vibrations aspects, the characterization of large bubble flow pattern would not be important, since this flow pattern does not promote excessive test section vibrations, and there is no variation of pressure drop trends, as presented by Kanizawa and Ribatski (2014);
- A comparison between flow patterns identified experimentally and predicted by the flow pattern maps was presented. The method of Ulbrich and Mewes (1994) provided the best predictions of the experimental database, predicting 83.3 and 73.0 % of experimental flow pattern identified through subjective and objective methods, respectively. All methods evaluated presented worse prediction for the flow patterns identified objectively than subjectively, and this can be attributed to the fact that all methods used databases comprising flow patterns identified subjectively for their development.

5 ACKNOWLEDGEMENTS

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