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An experimental study on gas and liquid separation at Y-junction tubes by pressure control

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ABSTRACT
An experimental investigation on gas and liquid separation at Y-junction tubes was conducted to explore whether it is viable to keep Y-junctions in good operational condition by pressure control. In the experiments, four junctions were combined in series, all with a 60° upward branch. The results show that there exists a critical value for the pressure drop ratio to make the system perform best, and the pressures at the inlet and both outlets play a significant role in the separation efficiency. Furthermore, a new relationship has been developed for the prediction of the phase split at Y-junction tubes.

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Air–water separation; pressure control; Y-junction tubes

Introduction

Traditionally, the petroleum industry has utilized conventional vessel-type separators, relying on gravity and expansion, to separate natural gas from multiphase mixtures, and they are bulky, heavy, and expensive. With the rise of offshore oil development, space restrictions cause conventional separating devices to no longer meet the requirements of applications. Thus, researchers have expressed strong interest in developing compact alternatives that are small, low weight, low cost, and efficient. T-junction tubes may be a potential solution to the need.[1,2]

In the T-junction tubes, the straight arm is defined as the run, and the lateral arm is defined as the branch. Based on the Bernoulli effect, there is a reversible pressure rise at the run and at the branch for the deceleration of the fluid as a part of the fluid is diverted into the branch. However, the reversible pressure rise at the branch is smaller than the irreversible pressure drop, while it is exactly the opposite at the run. Therefore, the pressure at the entrance of the run is higher than that of the branch, which provides the driving forces for the fluids moving from the inlet into the branch arm.[3–5] These driving forces are the source of the centripetal forces at a T-junction proposed by Shoham *et al.*[6] and Hwang *et al.*[7], and the balance between this driving force and the inertia force determines the flow directions of the gas and liquid. As is known, the gas phase has less inertia than the liquid phase, so the gas can be expected to more easily turn the corner into the branch. When the branch is inclined, the effect of gravity can resolve the phase maldistribution more effectively than the result obtained in horizontal T-junctions.[8,9] In addition to the orientations of the inlet and outlets, the phase split at a T-junction is significantly affected by the flow pattern upstream of the junction,[10–12] the inlet phase superficial velocities,[13,14] the system pressure,[15,16] the branch angle,[7,17] and the insertion of baffles.[18,19] Most of the work done in the past was based on the influence of these factors, and there has been very little work published considering the relationship between the pressure drop and the separation performance of T-junctions.

As a T-junction may not achieve full separation, combining T-junctions is necessary to obtain a high degree of separation. Bevilacqua *et al.*[20] first proposed the concept of combining two or more T-junctions to achieve the desired separation effects. Wren and Azzopardi[21] placed two oppositely orientated vertical T-junctions in series and compared the separation capabilities of different outlet combinations with that of each junction. The results showed that the separation performance of the system with two T-junctions was better but more complex than that of a single junction. According to the separation requirements, various separation qualities could be achieved by using different junction combinations. However, the separation system failed to meet the suggested target separation criterion, for more than 10% by volume of the liquid exited with the gas stream. To solve these problems, Baker *et al.*[22] replaced the butterfly valves positioned at the three outlets with two control valves, one optimizing the liquid residence time and the other associated with an automatic level control. Using this junction

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system, they observed that temporary unexpected flow regimes seriously affected the separation and the resultant flow split showed highly nonlinear characteristics.[23]

When the geometry of a T-junction separator is optimal, regulating the split ratio can further enhance the natural phase separation.[24,25] However, a slight change in the pressure at each outlet can have a significant impact on the flow rates.[20] In addition, the measurement precision of a common gas–liquid two-phase flowmeter is low; so it is very difficult to keep the flow rates at the two outlets at their desired values. Furthermore, in real production, the mixture flows are not at steady state, and the flow rates and gas–liquid ratio always vary with time.[23] The maldistribution at the T-junctions changes significantly when the inlet flows are altered, which is the major problem in the use of T-junctions as phase separators for gas–liquid flows.[26] In consequence, a separation system cannot be stably operated under its optimal conditions merely by regulating the split ratio. Therefore, the objective of this work is to design a compact Y-junction separator by combining several junctions in series, and it presents a pressure control scheme instead of flow rate control to maximize the separation performance over a wide range of inlet flow conditions.

Experimental investigation

Flow loop

The experimental facility is illustrated in Fig. 1. In the flow loop, air was chosen as the gas phase, while water was chosen as the liquid phase. The physical properties under the experimental conditions were as follows: ρ_g = 1.205 kg/m^3, μ_g = 1.81×10^{-3} mPa·s, ρ_w = 998.0 kg/m^3, μ_w = 1.0 mPa·s. The inlet air flow rate to the mixer was controlled by using a butterfly valve and then metered by a calibrated variable-area rotameter. The inlet water flow rate to the mixer was controlled by regulating the pump speed and then metered by a calibrated turbine flowmeter. The Y-junction tubes used in this experiment consisted of four junctions. All the branch arms were orientated in the same direction of 60° upwards, *i.e.*, Y-junctions. For mixture flows with a low liquid velocity, the separation performance was relatively independent of the inclination angle for $30° < \theta < 90°$. However, the inclination angles showed a great influence on the separation performance for $0° < \theta < 30°$.[27] Therefore, the present study chose an inclination angle of 60° to avoid this sensitive interval. All the tubes were fabricated from plexiglass to enable visual observation and were 50 mm in diameter.

To obtain the separation efficiency, each phase flow rate of the mixtures emerging from each outlet was metered online by Coriolis mass flowmeters. The pressures at the inlet and each outlet were controlled by using butterfly valves and metered by pressure taps (12 mm diameter) inserted in the test sections. As shown in Fig. 1, the pressure taps at the inlet, run, and branch were respectively located at the tubes 132.5 mm in front of the center line of the first Y-junction below, 132.5 mm behind the center line of the fourth Y-junction below, and 132.5 mm behind the center line of the fourth Y-junction above. After the measurements, the air and water two-phase flow at each outlet was directed to its respective mixture tank for further separation. The separated air was discharged to the atmosphere, and the separated water was returned to the storage tank for cyclic utilization.

Experimental procedure

The experimental procedure was designed to explore the physical laws of pressure control at various inlet conditions. To begin with, all the valves were fully opened, and then the air compressor and the centrifugal pump were switched on. The inlet flow rates of water and air were set to the desired values by adjusting the pump speed and the butterfly valve at the air inlet. Then, the diaphragm valves at both outlets were adjusted to the proper positions, where both the liquid fraction at the branch and the gas fraction at the run

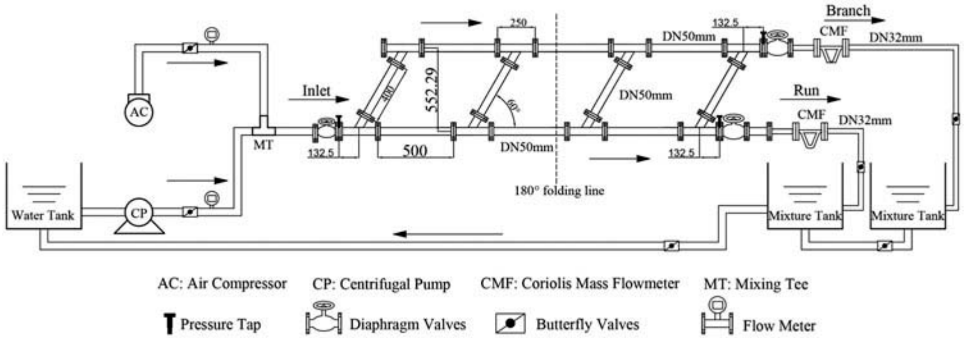


Figure 1. Schematic diagram of the flow loop.

were near zero. After that, the diaphragm valve at the run remained untouched, while the diaphragm valve at the branch was slowly regulated at its opening to obtain phase-split parameters under different operating conditions. When the inlet flow rate was different from the desired value, it was regulated again. In the process, the inlet and outlet flow rates and pressures were recorded by a data acquisition card. For different inlet conditions, the whole procedure was repeated.

Experimental conditions

Thirteen sets of inlet conditions were employed in this work, covering a wide range of inlet volume void fractions between 0.17 and 0.61. The tests could be divided into three groups: constant inlet liquid flow rate and different inlet gas flow rates, constant inlet gas flow rate and different inlet liquid flow rates, and constant inlet mixture flow rate and different inlet gas and liquid ratios. Detailed information is presented in Table 1. All experiments were carried out at room temperature. It should be mentioned that the superficial velocities of the gas, liquid, and mixture at the inlet are calculated from the standard definitions:

$$V_{sg}=\frac{Q_{g1}}{\pi d^2/4} \tag{1}$$

$$V_{sl}=\frac{Q_{l1}}{\pi d^2/4} \tag{2}$$

$$V_m=\frac{Q_{g1}+Q_{l1}}{\pi d^2/4} \tag{3}$$

where Q_{g1} is the total amount of gas at the inlet, Q_{l1} is the total amount of liquid at the inlet, and d is the diameter of the tubes.

Table 1. Actual inlet conditions for each test.

Case	Inlet volume void fraction	Inlet liquid flow rates (m^3/h)	Inlet gas flow rates (L/min)	Inlet mixture flow rates (L/min)	Inlet pressure (kPa)
1	0.26	3.33	20	75.5	14–21
2	0.26	3.33	20	75.5	15–65
3	0.35	3.33	30	85.5	13–22
4	0.35	3.33	30	85.5	16–69
5	0.42	3.33	40	95.5	15–37
6	0.47	3.33	50	105.5	18–47
7	0.52	3.33	60	115.5	18–58
8	0.17	5.73	20	115.5	49–52
9	0.26	5.13	30	115.5	17–43
10	0.35	4.53	40	115.5	15–34
11	0.43	3.93	50	115.5	15–29
12	0.61	2.73	70	115.5	15–28
13	0.30	5.73	40	135.5	25–114

Results and discussion

Effects of pressure drop ratio on phase split

The pressure drop ratio is defined as the ratio of the inlet-to-branch pressure drop to the inlet-to-run pressure drop:

$$\overline{\Delta P}=\frac{P_1-P_3}{P_1-P_2} \tag{4}$$

where P_1, P_2, and P_3 are the pressures measured by the pressure taps at the inlet, run, and branch, respectively.

The gas fraction at the run is expressed as

$$F_{g2}=\frac{Q_{g2}}{Q_{l2}+Q_{g2}} \tag{5}$$

where Q_{g2} is the gas flow rate at the run and Q_{l2} the liquid flow rate at the run.

Under various inlet conditions that can easily be realized, the run outlet liquid stream is almost free of gas.[28] Additionally, in the present experiment, all the gas can soon run into the branch in the form of bubbles, as shown in Fig. 2. After the phase separation, the gas fraction at the run is generally less than 1‰ (Fig. 3). Therefore, this paper mainly studies the liquid separation efficiency, namely the amount of liquid at the branch outlet gas stream. Here, the separation efficiency (η) is defined to evaluate the performance of the Y-junction tubes in Eq. (6):

$$\eta=1-\frac{Q_{l3}}{Q_{l1}} \tag{6}$$

where Q_{l3} is the amount of liquid entrained in the outlet gas stream.

Figure 4 shows the change in separation efficiency with the pressure drop ratio for five groups of experimental data. As seen, the separation efficiency decreases

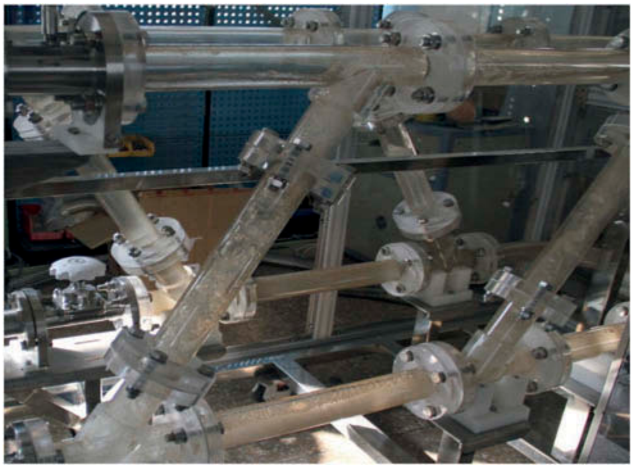


Figure 2. Fast rising bubbles.

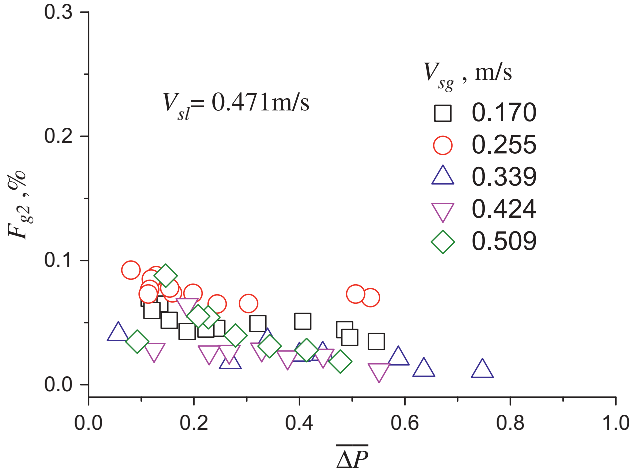


Figure 3. Low gas fraction at the run.

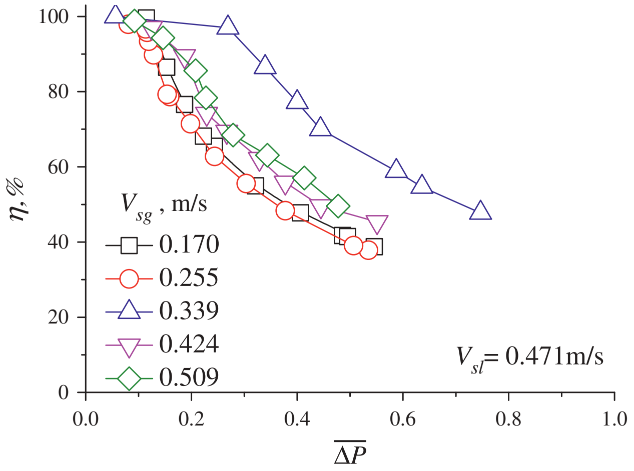


Figure 4. Effects of pressure drop ratio on separation efficiency.

with the increase in the pressure drop ratio. This phenomenon can be explained physically through the back-pressure at both outlets. The decrease of the pressure drop ratio means that the back-pressure at the run drops or that at the branch increases. Both can make fluids more likely to flow out through the run, whereas the liquid level in the Y-junction tubes maintains a certain value, providing a barrier against the gas at the branch flowing into the run, as shown in Fig. 5. At the same time, the residence time of the liquid at the branch will increase so that the liquid falls into the run more easily from the Y-junction tubes, especially when encountering high-momentum liquid slugs, as shown in Fig. 6. Thus, the gas stream generated at the branch will become less contaminated with liquid, and the separation efficiency will thereby be promoted. However, when the pressure drop ratio decreases to a certain extent, the gas fraction at the run will rapidly increase due to the lowering of the liquid level, as shown in Fig. 7. It can be determined that there exists a critical value for the pressure drop ratio at which the Y-junction tubes perform the best.

Figure 5. The liquid level in the Y-junctions tubes.

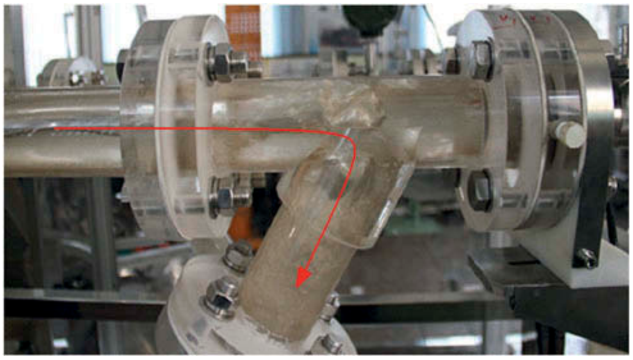


Figure 6. The liquid falling into the run.

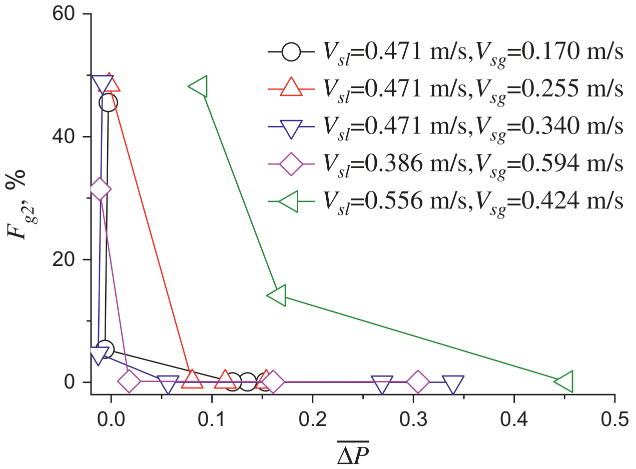


Figure 7. Effect of pressure drop ratio on gas fraction at the run.

Effects of the dimensionless pressure on the phase split

In the present study, the dimensionless pressure is defined as the ratio of the inlet-to-branch pressure drop to the pressure at the run:

$$\bar{P} = \frac{P_1 - P_3}{P_2} \tag{7}$$

where P_1, P_2, and P_3 are the pressures measured by the pressure taps at the inlet, run, and branch, respectively.

Figure 8 shows the separation efficiency versus pressure drop ratio or dimensionless pressure under the conditions of constant inlet gas and liquid flow rates and different inlet pressures (P_1). It is observed in Fig. 8(a) and 8(b) that the curves do not coincide, and the system pressure has a great influence on the separation performance. The same phenomenon was observed in the works of Van Gorp *et al.*[15] and Das *et al.*[16]

To reflect the physical laws more closely, the dimensionless pressure ($\bar{P}$) is proposed by considering the system pressure. As seen in Fig. 8(c) and 8(d), the data points in each experiment basically overlap. By comparing these figures, it can be determined that the dimensionless pressure more closely reflects the objective laws of pressure control. To reveal the relationship between the dimensionless pressure and the system separation performance, a systematic measurement was performed for various combinations of superficial gas and liquid velocities, as listed in Table 1. All the phase split parameters for each set were measured over a period of 60 seconds, with a reading taken every 0.001 second. The flow rates and pressure were taken as the average of 60-second data sets. The separation efficiency versus the dimensionless pressure is depicted in Fig. 9. It can be seen that these curves show similar trends, and the separation efficiency increases as the dimensionless pressure decreases. Another distinct observation is that all the data are concentrated around a certain curve, independent of the inlet superficial velocity. This means that the separation performance of the Y-junction system is strongly dependent on the pressures at the inlet and both outlets. In addition, the data points in Fig. 9(a) are more compact than those in Fig. 9(b) and 9(c). Thus, the phase split at the Y-junctions is less affected by the inlet gas superficial velocity than by the inlet liquid superficial velocity.

Predictive relationship

In this work, the optimal pressure control strategy is that at which the separation efficiency reaches almost its maximum value while the gas fraction at the run is near zero. Figure 10 presents the optimum dimensionless pressure ($\bar{P}_{\text{opt}}$) for various inlet conditions. With all other valves untouched, the control valve at the branch

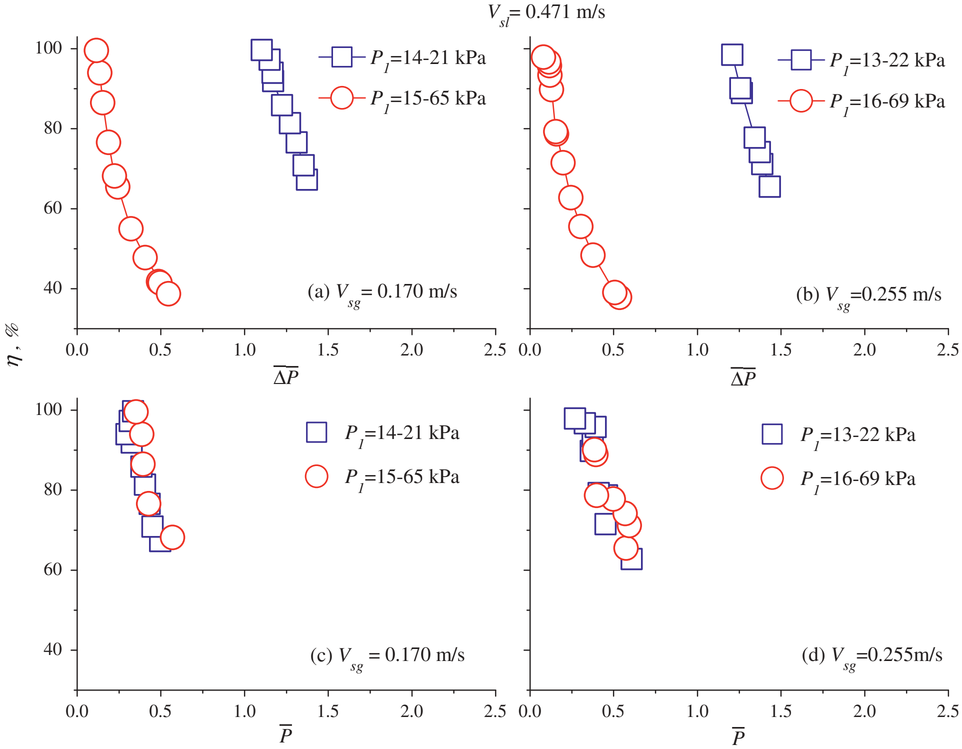
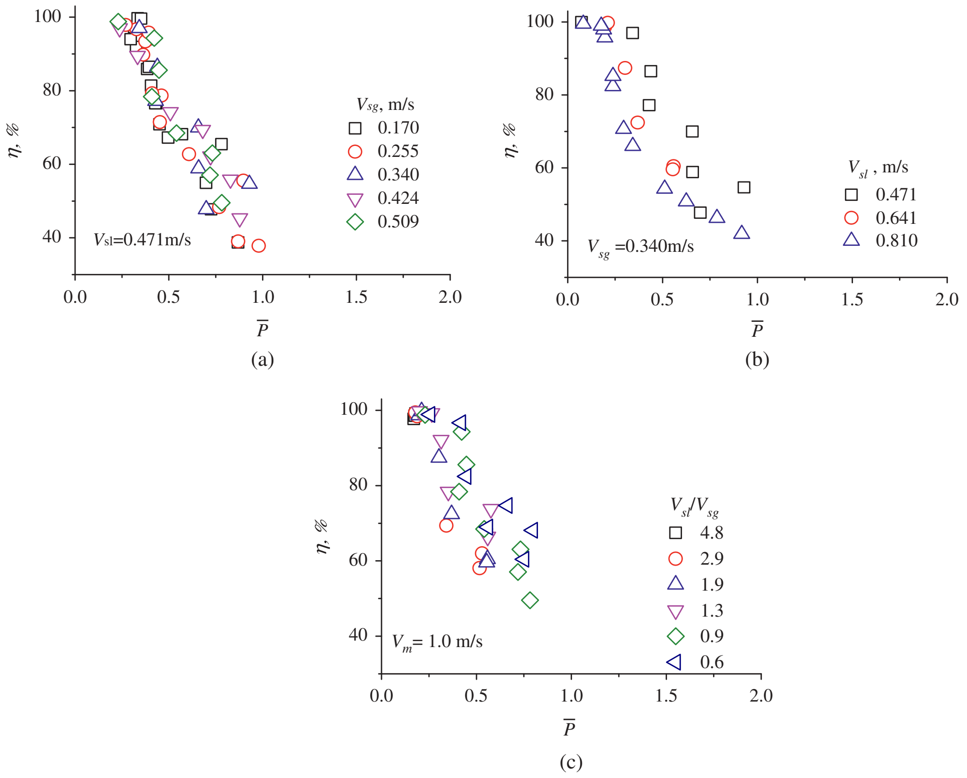


Figure 8. Separation efficiency versus pressure drop ratio or dimensionless pressure.



(a) (b) (c)

Figure 9. Separation efficiency versus dimensionless pressure for various inlet conditions: (a) Constant inlet liquid flow rate and different inlet gas flow rates, (b) constant inlet gas flow rate and different inlet liquid flow rates, and (c) constant inlet mixture flow rate and different inlet gas and liquid ratio.

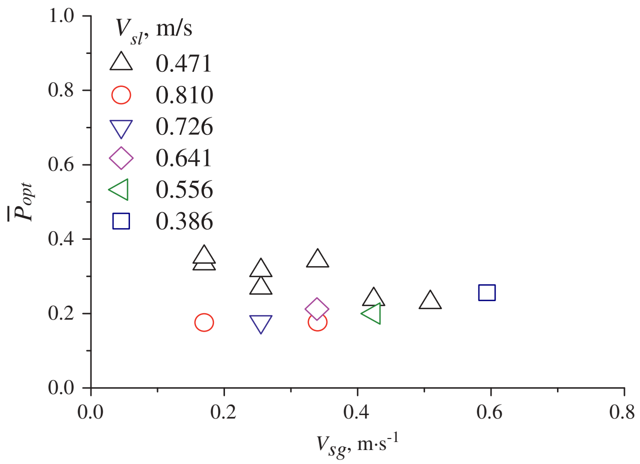


Figure 10. Optimum dimensionless pressure for various inlet conditions.

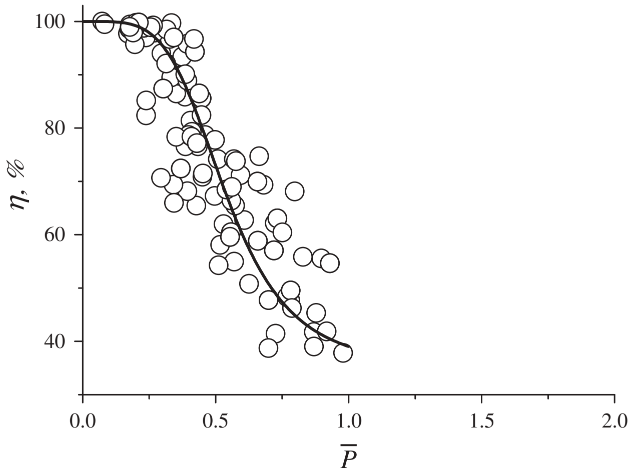


Figure 11. The curve obtained by fitting all the data.

was regulated gently to obtain the optimal pressure control strategy during each test. For all cases, more than 97% of the data are located in a relatively narrow range from 0.176 to 0.352. This also demonstrates that a pressure control strategy for the operation of Y-junctions is feasible.

Figure 11 shows the change in the separation efficiency with the dimensionless pressure. It can be seen that the data are very concentrated. This phenomenon can be explained physically through the main physical variables that influence the system separation performance. Just as in a traditional hydrocyclone, the phase split at Y-junctions can be controlled by the pressure drop. However, at the same time, gas is compressible, so the system pressure also has a significant influence on the gas and liquid separation performance at Y-junctions. In this work, the inlet-to-branch pressure drop represents the system pressure drop and the pressure at the run represents the system pressure, and thus a dimensionless number can be constructed by using these three pressures. Therefore, the separation efficiency can be strongly affected by the dimensionless pressure (Eq. (7)).

The curve in Fig. 11 can be roughly divided into two stages. First, the curve changes show an approximately straight line, and the separation efficiency decreases exponentially with the dimensionless pressure. The relationship between the separation efficiency and the dimensionless pressure can be re-extracted from the present experimental data as

$$\eta = 0.35 + \frac{0.65}{1 + (\bar{P}/0.54)^{4.4}} \tag{8}$$

where the number of experimental points used is approximately 123 and the developed predictive relationship gives a reasonable performance, with 86% of the data having an average absolute error less than 20%. To further confirm the validity of the suggested model, the results of the predicted values compared to the experimental data reported by Bevilaqua *et al.*[20] are presented in Fig. 12. The separation configuration they used consisted of two T-junctions and one Y-junction (57 mm diameter). Here, the number of experimental points used is 36, and 89% of the data have an average absolute error less than 20%. Thus, the suggested model is also applicable to similar configurations for gas and liquid separations.

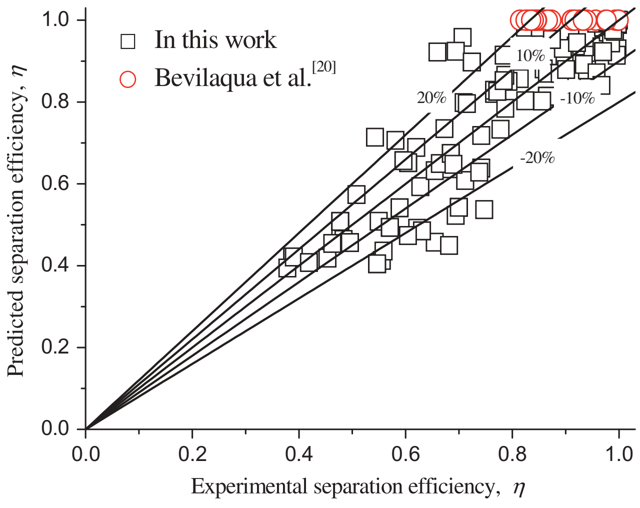


Figure 12. Comparison between experimental and predicted separation efficiency.

This empirical equation is of great significance to field applications in the oil and gas industry. It can help set the pressures at the inlet and both outlets to maximize the fractional amount of inlet liquid extracted into the run, and the composition of the gas–liquid mixture after separation can be determined approximately by using this empirical equation.

Conclusions

The use of a Y-junction system for gas and liquid separation is attractive since it is small, low weight, and low cost. To make the Y-junction system work efficiently, an experimental study was performed to explore the rule of pressure control. The following conclusions are summarized:

For gas and liquid separation using Y-junctions, there exists a critical value for the pressure drop ratio at which the system performs best, and the pressures at the inlet and both outlets play significant roles in the separation efficiency. Compared with the superficial gas velocity, the superficial liquid velocity shows more serious effects on the phase split.

Based on the present data, a predictive relationship between the separation efficiency and the dimensionless pressure was developed. The conclusions reveal that the relationship presents good agreement. Considering that a more accurate prediction would be significantly more complicated and difficult, the model suggested might be helpful for practical applications in industry, especially for the design of tube separators.

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