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2018,30(1):173-176
https://doi.org/10.1007/s42241-018-0019-4

Gas-liquid flow splitting in T-junction with inclined lateral arm *

Le-le Yang(杨乐乐), Shuo Liu(刘硕), Hua Li(李华), Jian Zhang(张健),
Ying-xiang Wu(吴应湘), Jing-yu Xu(许晶禹)
Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
School of Engineering Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

(Received June 21, 2017, Accepted November 13, 2017)

Abstract: This paper studies the gas-liquid flow splitting in T-junction with inclined lateral arm. The separation mechanism of the T-junction is related to the pressure distribution in the T-junction. It is shown that the separation efficiency strongly depends on the inclination angle, when the angle ranges from 0^{o} to 30^{o}, while not so strongly for angles in the range from 30^{o} to 90^{o}. Increasing the number of connecting tubes is helpful for the gas-liquid separation, and under the present test conditions, with four connecting tubes, a good separation performance can be achieved. Accordingly, a multi-tube Y-junction separator with four connecting tubes is designed for the experimental investigation. A good agreement between the simulated and measured data shows that there is an optimal split ratio to achieve the best performance for the multi-tube Y-junction separator.

Key words: Gas-liquid separation, T-junction, numerical simulation, split ratio

The tee junctions are widely used in petroleum and chemical industry. When a gas-liquid two-phase flow is introduced into the tee junctions, one almost inevitably sees the phase mal-distribution, with serious consequences on the behavior of the downstream equipment. However, the tee junctions can serve as a partial phase separator when this natural phase mal-distribution is enhanced. As a partial phase separator, the tee junctions have an obvious advantage in the size. However, for a simple tee junction, it is difficult to prevent the liquid emerging from the lateral arm. Based on an extensive literature review, Saieed et al.[1] suggested to explore a combination of more than one tee junctions for the phase separation.

A large number of variables influence the phase separation at the tee junctions, and the separation mechanism remains an issue to be studied[2]. The methods for studying the flow splitting in the T-junction can be basically divided into three categories. For the first category, experimental laws are used to obtain empirical correlations by fitting experimental data[3, 4]. For the second category. phenomenological models are established[5, 6]. The methods of these two categories are only applicable under particular operating conditions and with special tee junction geometries. Therefore, we have to consider the third category: using numerical simulations.

In the present study, the gas-liquid flow splitting in the T-junction with inclined lateral arm is numerically simulated to investigate the detailed phase mal-distribution phenomena, focusing on the effects of the inclination angles and the number of connecting tubes on the phase split. Based on the numerical simulation results, a compact multi-tube Y-junction separator with four connecting tubes is designed to achieve a good gas-liquid separation performance. To verify the numerical model, the experimental results obtained by this separation system are compared with numerical simulation results.

The Euler-Euler approach is widely used to simulate the multiphase flow[7]. In the Euler-Euler approach, with a mixture model, the concept of the slip velocity is used to allow the phases to move at different speeds. The standard k-ε model is chosen to model the turbulent flow. The diameter of all pipes in the geometrical model is 0.05 m. A 2.50 m long pipe is set before the inlet to ensure the full develop-

* Project supported by the National Natural Science Foundation of China (Grant No. 51779243), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No: XDb22030101).
Biography: Le-le Yang (1992-), Male, Ph. D. Candidate,
E-mail: yanglele@imech.ac.cn
Corresponding author: Hua Li,
E-mail: lihua@imech.ac.cn

ment of the gas-liquid flow. In this study, the air and the water are used as the working fluids, with physical properties as follows: $\rho_g = 1.21\ \text{kg/m}^3$, $\mu_g = 1.81 \times 10^{-3}\ \text{mPa}\cdot\text{s}$, $\rho_l = 998.00\ \text{kg/m}^3$, $\mu_l = 1.00\ \text{mPa}\cdot\text{s}$. The model inflow boundary is the uniform velocity inlet. At both outlets, the free outlet boundary is employed. The near-wall flow is resolved by the standard wall function.

The inlet, the straight arm, and the lateral arm gas volume fraction are calculated by

$$\alpha_i = \frac{Q_{gi}}{Q_{gi} + Q_{li}}, \quad i = 1\text{-}3 \tag{1}$$

where Q_{gi} is the gas flow rate, Q_{li} the liquid flow rate, and the subscripts 1-3 refer to the inlet, the straight arm, and the lateral arm.

The split ratio is defined as the ratio of the mixture flow rate at the lateral arm to that at the inlet as follows

$$F_3 = \frac{Q_{g3} + Q_{l3}}{Q_{g1} + Q_{l1}} \tag{2}$$

The superficial velocity of the mixture at the inlet is calculated according to the standard definition

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

where d is the diameter of the tubes.

In order to evaluate the phase separation performance of the T-junction separator, the separation efficiency proposed by Yang et al.[8] is employed as

$$\eta = \left| \frac{Q_{g3}}{Q_{g1}} - \frac{Q_{l3}}{Q_{l1}} \right| \tag{4}$$

Numerical results show that the pressure at the inlet is higher than that at the lateral arm but lower than that at the straight arm, because of the deceleration of the fluid while flowing through the T-junction. Due to the Bernoulli effect, there is a reversible pressure rise at the straight arm and the lateral arm. Various vortices are produced at the place where the fluid just enters the lateral arm, to cause a large pressure drop with turbulence and energy losses. Thus, the irreversible pressure drop at the lateral arm is larger than the reversible pressure rise. Meanwhile it is exactly the opposite at the straight arm. Thus we will have a pressure drop at the lateral arm and a pressure recovery at the straight arm, to provide centripetal forces for the fluids to turn into the lateral arm. In the gas phase, the inertial force is larger than the centripetal force, which makes the gas phase preferentially flow into the lateral arm. Conversely, it is harder for the liquid phase to change direction and exit through the lateral arm than the gas phase.

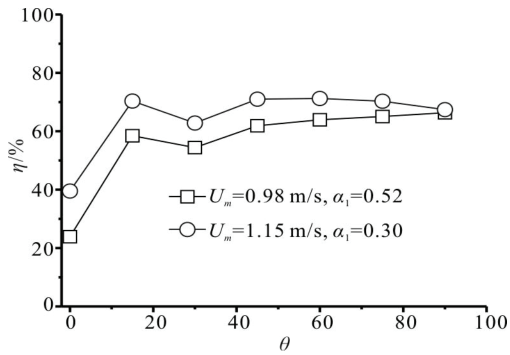


Fig. 1 Effect of inclination angles on phase split

In order to investigate the effect of the inclination angles (θ) on the phase split, the gas-liquid separation behavior in different connecting structures in the angle range of $0^\circ < \theta < 90^\circ$ is simulated. Numerical results show that the flow of the gas-liquid mixture in the lateral arm is an approximately stratified flow for small inclination angles. With the increase of the inclination angle, the flow of the gas-liquid mixture in the lateral arm becomes a homogeneous flow. The reason is that the lateral arm is similar to a horizontal tube when the inclination angle is small. With the effect of gravity, the liquid subsides to the bottom of the tube while the gas rises to the top of the tube. The angle between the gravity and flow directions of the gas-liquid mixture will increase with the increase of the inclination angle, which will result in a reversed flow and strengthen the flow instability. Figure 1 shows the effect of the inclination angles on the phase split. It can be seen that the inclination angles have little impact on the phase split in the range of $30^\circ < \theta < 90^\circ$. However, the phase split is quite sensitive to the change of the inclination angles in the range of $0^\circ < \theta < 30^\circ$. This phenomenon can be explained through the intersecting lines. When the inclination angle is 0°, the gravity has little effect on the flow direction of each phase. When the inclination angle is more than 0°, the gravity effect will prevent the liquid from flowing into the lateral arm. Meanwhile, the intersecting line of the T-junction is long when the inclination angle is small. So the gas on the top of the tube has more chance to flow into the lateral arm, namely, the separation efficiency is promoted. But the lengths of the intersecting lines are basically the same in the range of $30^{\circ} < \theta < 90^{\circ}$, thus the separation performance is also similar. In order to avoid the sensitive interval, an inclination angle of 60° is chosen in the following study.

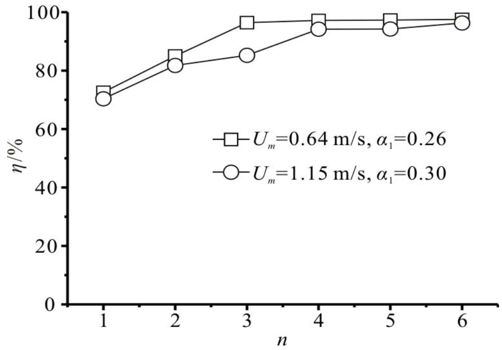


Fig. 2 Effect of the number of connecting tubes on the phase split

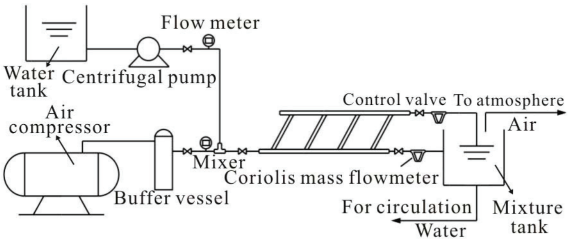


Fig. 3 Schematic diagram of the flow loop

Figure 2 shows the effect of the number of connecting tubes on the phase split. It can be seen that the greater the number of connecting tubes (n) is, the better the separator performs. The number of Y-junctions will increase with the increase of the number of connecting tubes. We will see the phase mal-distribution, when the gas-liquid mixture flows through each Y-junction. At the same time, with more connecting tubes, we will have more space. The velocity of the gas-liquid mixture decreases, thus the residence time in the multi-tube Y-junction separator will increase, so the gas will have more chance to separate from the liquid. Therefore, better separation performance can be achieved if the number of connecting tubes increases. However, with more connecting tubes, the structural characteristics of the pipeline type separator are bound to be lost. Besides, it can be seen in Fig. 2 that the multi-tube Y-junction separator performs very well when the number of connecting tubes reaches four under the present test conditions. Namely, there are still exchange of mass, momentum and energy between the straight arm and the lateral arm at the third connecting tubes. After the third connecting tubes, the flow becomes basically steady.

Based on the above research results, a multi-tube Y-junction separator with four connecting tubes is designed for the experimental investigation. The angle between the straight arm and the lateral arm is 60°, and the pipe diameter is 0.05 m. A schematic diagram of the flow loop is illustrated in Fig. 3. The air is drawn from the air compressor and metered by a calibrated rotameter while the water is pumped from the water tank and metered by a calibrated turbine flowmeter. Then the air and the water are mixed by a simple mixing tee. After separation through the multi-tube Y-junction separator, the gas fraction and the mixture flowrate at both outlets are metered by Coriolis mass flowmeters.

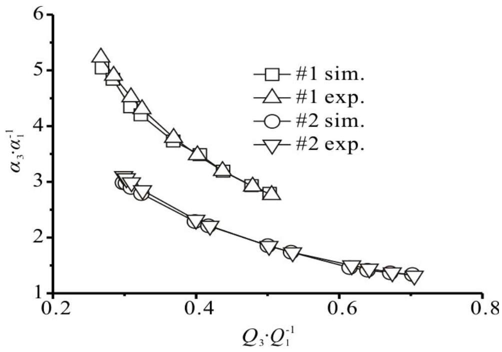


Fig. 4 Comparison between numerical and experimental results

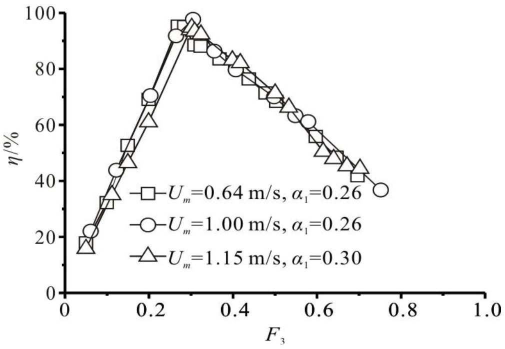
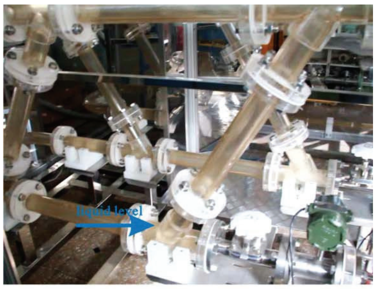


Fig. 5 Effect of split ratio on separation efficiency

In the numerical simulation, the flow rates, the physical properties and the boundary conditions are set according to the practical experimental conditions. The numerical simulation results of the multi-tube Y-junction separator with four connecting tubes are compared with the corresponding experimental results (Fig. 4). In run #1, the mixture velocity (U_m) is 0.64 m/s and the gas fraction (α_1) is 0.26. In run #2, $U_m = 1.15$ m/s and $\alpha_1 = 0.30$. It can be seen that the prediction results of the numerical simulation are in a good agreement with the experimental measurements. Therefore, the model used in this study is adequate to predict the gas-liquid separation behavior in the multi-tube Y-junction separator with several connecting tubes, which is helpful to design the tube separator for practical applications in industry.



(a)F_3=0.10

(b)F_3=0.26

(c)F_3=0.48

Fig. 6 (Color Online) Gas-liquid flow splitting in multitube Y-junction separa- tor for different split ratios

Figure 5 shows the effect of the split ratio on the separation efficiency for three groups of numerical results. As can be observed, the separation efficiency firstly increases and then decreases with the increase of the split ratio. Namely, there is an optimal split ratio for the best performance of the multi-tube Y-junction separator. Figure 6 indicates the splitting of the gas-liquid flow in the multi-tube Y-junction separator for different split ratios. When the split ratio is fairly small, the liquid level is very low, with an amount of the gas flowing through the straight arm. As the split ratio increases, more gas flows into the first lateral arm. And due to the hydraulic jump, the liquid level rises in the lateral arm. Then the liquid will be carried into the gathering tube with the rising gas stream through the first lateral arm and drains into the subsequent lateral arm. However, the liquid level will provide a barrier preventing the gas at the gathering tube from flowing back into the straight arm. In this case, the complete separation is almost achieved. If the split ratio increases further, the gas stream will carry more liquid into the lateral arm. At the same time, the residence time of the liquid at the gathering tube will decrease, which makes it more difficult for the liquid to fall into the straight arm. This process will lead an amount of the liquid to exit with the gas stream from the lateral arm and an amount of the pure water to emerge from the straight arm.

A numerical and experimental investigation of the gas-liquid flow splitting with inclined lateral arm is conducted. The separation mechanism of the T-junction is studied by numerical simulations. A balance between the inertial force and the centripetal force is found to determine the direction of the gas and liquid two phase flow. The simulation results show that the separation efficiency strongly depends on the inclination angle for angles ranging from 0^{o} to 30^{o}, while not so strongly for angles ranging from 30^{o} to 90^{o}. The multi-tube Y-junction separator performs better with the increase of the number of connecting tubes. Under the present test conditions, the multi-tube Y-junction separator performs very well when the number of connecting tubes reaches four. Experimental and numerical results show that there is an optimal split ratio for the best performance of the multitube Y-junction separator.

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