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Investigation of the Gas−Liquid Two-Phase Flow and Separation Behaviors at Inclined T-Junction Pipelines

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Cite This: *ACS Omega* 2020, 5, 21443−21450

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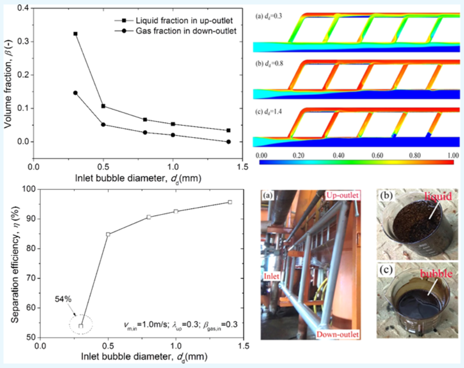
ABSTRACT: The T-junction is a novel type of separator used in the petroleum and gas industry. It is used to achieve the gas−liquid or liquid−liquid two-phase separation. To obtain an applicative T-junction separator, in the present study, the gas−liquid two-phase separation characteristics in multiple inclined T-junctions were investigated through a series of numerical simulations and field experiments. Two representative multiphase modes, namely, the Euler model and the mixture model, were chosen for this study. Comparisons of the field experiments were made to obtain a highly accurate simulation model. The mixture model was chosen to be better suited for this study. It is used to investigate the gas−liquid two-phase flow and the separation behaviors, which include the effect of inlet flow velocity, inlet bubble diameter, and the split ratio of two outlets. The results indicate that the best flow split ratio exists when the two-phase separation reaches the best consequence, and the best flow split ratio changes when the separation demands of gas or liquid are different. Furthermore, the separation efficiency keeps decreasing as the inlet velocity is increased. Hence, the inlet mixture velocity should be reduced to improve the gas−liquid two-phase separation. More specifically, to obtain a better separation for the same throughput, the size of the T-junction should be increased. Moreover, the separation efficiency increases as the inlet bubble diameter increases. Consequently, the results can be used to design the T-junction as an industrial separator, which can then be directly used in petroleum and gas production.



1. INTRODUCTION

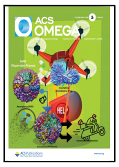
In the petroleum and gas industry, the pipeline transportation system is one of the main methods used in modern energy transport.[1] Gas and liquid are generated simultaneously at the producing wells. The flow redistribution phenomenon occurs when the gas−liquid two-phase flow through the T-junction, and both flow rate and phase volume fractions change due to the gravity and different backpressures of the two outlets.[2,3] Therefore, the T-junction has been suggested as a separator to achieve the gas−liquid or liquid−liquid two-phase separation.[4] Compared to the traditional vessel separator, the T-junction can decrease the pressure drop and increase the speed of separation. Furthermore, the compact size of the T-junction separator is smaller than the vessel separator, and the costs related to building the equipment are far less.

Over a considerable period of time, numerous researchers have attempted to obtain an applicative T-junction separator for the two-phase separation. The majority of the researches have attempted to initially improve the efficiency of separation by focusing on the optimal geometry. Following this, the separation phenomenon has been modeled, and applicability in the industry has been continually investigated. Moreover, these research studies have been developed from single T-junction to multiple T-junctions.

Seeger et al.[5] displayed that due to different inlet flow patterns, the flow parameters varied over a wide range. Additionally, Azzopardi and Whalley[6] studied the effect of the inlet flow pattern on a two-phase flow in a T-junction. The results showed that the separation phenomenon is dependent on the upstream flow pattern. It was exhibited that if the flow pattern is bubbly, the gas would preferentially enter the sidearm. In most other researches, the inlet flow pattern of the T-junction was always controlled, either as stratified or slug flow, these have the greatest efficiency of the two-phase separation.

In addition, the effect of reducing the ratio of the sidearm on the flow and separate characteristics has been studied for a long time.[7] The results showed that the gas flow velocity in the taken-off branch of the T-junction could be increased by reducing the diameter of the sidearm. Hence, the pressure drop from the inlet to the sidearm outlet is increased, which is

Received: April 19, 2020
Accepted: August 6, 2020
Published: August 17, 2020



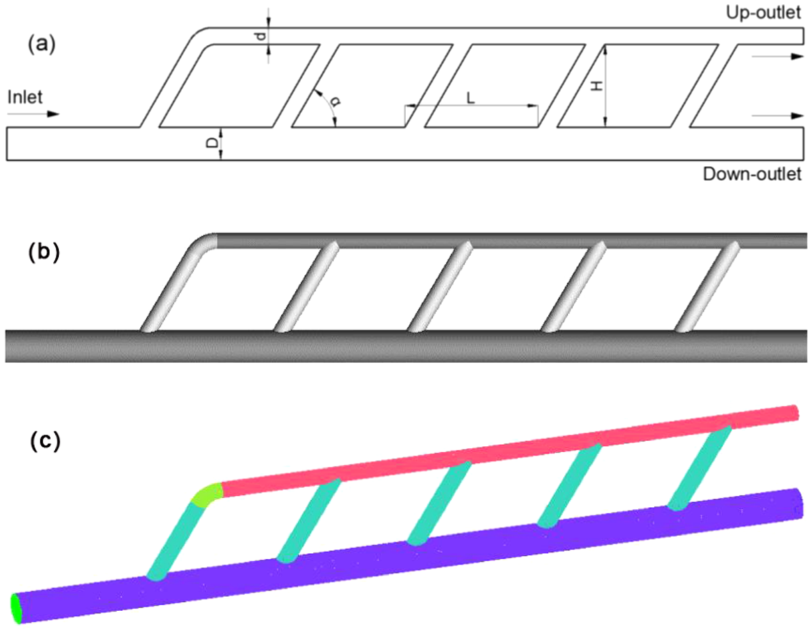


Figure 1. Geometry and its meshing result for numerical simulation: (a) geometry; (b) three-dimensional (3D) model; and (c) meshing structure.

conducive to gas separation. However, the acceleration of the gas flow will have some inertial influence on the liquid; as a result, the liquid could be dragged into the sidearm. Recently, Saieed et al.[8−10] conducted a series of experiments to investigate the effect of a reduced ratio on the gas−liquid separation at a single T-junction. In the experiments, five diameter ratios of the sidearm to the main pipe ranging from 1 to 0.2 were considered. Consequently, a reduced diameter ratio resulted in enhancing the phase maldistribution in stratified-wavy flow. The phase splitting performance of the T-junctions with different ratios in other flow regimes is yet to be explored.

Furthermore, the effect of the inclined angle of the sidearm on the gas−liquid separation was studied to improve the separation characteristics. Penmatcha et al.[11] displayed systematical research on the influence of the rotation angle of sidearm on the gas−liquid stratified flow in T-junction, the angle was from +35° above the horizontal to −60° below. It showed that a greater amount of liquid will be diverted into the sidearm by increasing the downward inclination, while most of the inlet gas will be diverted into the sidearm for an increased upward inclination. Moreover, a mechanistic model was devised to predict the splitting characteristics for the T-junction with an inclined sidearm. Yang et al.[12] reported that the inclined angle of the sidearm has a significant influence on the separation efficiency of a T-junction when the angle is in the range of 0−30°, it was also reported that the separation efficiency increased as the angle was increased. However, the effect is negligible when the inclined angle is larger than 30°.

Hence, since the flow and separation characteristics of the gas−liquid flow in a T-junction were obtained, the multiple T-junctions were developed in series as a separator to extend their application. Bevilacqua et al.[13] reported a multiple T-junction with three vertical sidearms, it was termed as a comb separator. Following this, Wren and Azzopardi[14] studied the gas−liquid separation capabilities of two T-junctions placed in a series in the configuration of one up-arm and one down-arm. It was demonstrated that the flow characteristic of the two T-junctions is more complex than that of a single T-junction, and there is a higher capability to separate the gas−liquid two-phase flow with more liquid-dominated inlet conditions. Yang et al.[15] reported a series of multiple T-junctions with two or three layers. The results obtained showed that the separation efficiency of multiple T-junctions is much higher than that of a single T-junction, and the separation efficiency was increased by increasing the number of vertical arms connected. The effect of the distance between each sidearm on two-phase separation was also available in the literature. Past studies have shown that increasing the interval between two side arms can improve the separation efficiency greatly.[16]

In the studies indicated above, the separation phenomenon of a T-junction was studied; however, the design method of the T-junction as a separator has not been researched. This gap has greatly restricted its industrial application. Currently, research on the T-junction can be classified into three directions. First, research has been performed on developing a theoretical model to describe or predict the two-phase separation phenomenon based on the existing consequences of the T-junction.[17] However, it is difficult to obtain a generalizable theory due to the complex inlet flow condition, and also because of the different kinds of geometry in T-junctions. Second, some researchers have investigated the industrial applicability of the T-junction as a two-phase separator.[18] It includes the researches on the design method and criterion for different industrial conditions. The third direction adopted by researchers is attempting to develop a numerical simulation method with great accuracy for the gas−liquid two-phase flow in a T-junction.[19,20]

In the present study, first, two kinds of multiphase flow numerical models, namely, the Euler model and the mixture model, are chosen to simulate the gas−liquid two-phase flow in multiple T-junctions. Following this, one of the two models will be obtained with increased accuracy through the comparison of results with experimental measurements. It is useful for designing the T-junction as a separator. The numerical simulation method has the potential for predicting the gas−liquid two-phase separation characteristics of a T-junction. Next, to obtain the effect factors and design method of the T-junction separator, the gas−liquid two-phase flow and separation behaviors in the inclined T-junction will be investigated by numerical simulation. In particular, the inlet of the T-junction will be displayed as a dispersed flow pattern to simulate industrial application. A series of influencing factors, such as the inlet flow velocity, particle size of the dispersed phase, and the split ratio of the two outlets, will be considered systematically. The results could be used to develop the design of a T-junction that is directly applicable as an industrial separator in the production of petroleum and gas.

2. VERIFICATION OF MULTIPHASE FLOW MODELS

2.1. Geometric Model of the T-Junction. In the present study, the inclined multiple T-junction is constituted by the down-horizontal pipe, up-horizontal pipe, and a number of connecting sidearms. Based on the research results in the literature, the effect of the inclined angle and diameter ratio on the separation characteristics of a T-junction has been clearly established. It has been shown that the separation efficiency may go up to its peak value when the angle α is less than 60°. Hence, the value of the angle α is set as 60°, and the diameter ratio of the sidearm and a down-horizontal pipe is set as 0.5, which is the optimal value for the gas−liquid two-phase flow conditions in this study. Increasing the number and interval of the connecting arms can improve the separation efficiency continually. Five-sided connecting arms are designed, and the distance between each sidearm is $4D$. It is sufficient to obtain all of the different separation phenomena in the T-junction.

Figure 1a displays the geometry of the inclined multiple T-junction. In summary, the diameter of the down-horizontal pipe (D) is 100 mm, the diameter of the up-horizontal pipe and these sidearms (d) is 50 mm, the interval of each side arm (L) is 400 mm, the distance between the up- and down-horizontal pipe (H) is 400 mm, and the inclined angle (α) is 60°.

Figure 1b,c illustrates the 3D geometry and the grid meshing result of the inclined multiple T-junction, respectively. To obtain all the characteristics of the gas−liquid two-phase flow and avoid the influence of the grid, the scale of the mesh generation was defined to be sufficiently small. This numerical geometry model contains about 2.95 million cells, and the maximum element is 3 mm.

2.2. Comparison of These Models. In this study, the Euler model and the mixture model were chosen to calculate the gas−liquid two-phase flow and separation phenomenon in the inclined T-junction. The result of simulating these models was compared with experimental results to choose a more accurate model for the subsequent research. As a result, a certain number of experimental results from the petroleum production field were used to make a comparison. The flow condition of the inlet and outlets of the T-junction was set on equal values. The velocity-inlet boundary was chosen, and a 1.0 m/s inlet mixture velocity for the gas−liquid mixture and the volume fraction of gas was set at 0.3. The diameter of the dispersed bubble in the inlet was set to 0.5 mm. To control the flow split ratio, the outflow boundary condition was chosen as the up and down outlets of the T-junction. The remaining boundaries were set as the wall with nonslipping. In this study, the RNG k-epsilon model was chosen as the viscous model, and the coupled and second-order upwind numerical methods were chosen to solve the relevant equations.

Table 1. Physical Properties of Gas and Liquid in This Work (T = 30 °C, P = 0.1 MPa)

	density, (kg/m^3)	viscosity (mPa s)	surface tension (N/m)
crude oil	900	240	0.042
gas	1.05	0.018	

Crude oil was chosen as the liquid phase for the comparative study between the experimental and simulation results. Table 1 displays the density and viscosity of the crude oil and gas. The flow split ratios of the up-outlet (λ_{up}) and the down-outlet (λ_{down}) were used to describe the operating parameter of the T-junction.

$$\lambda_{up} = \frac{Q_{up-outlet}}{Q_{inet}} \tag{1}$$

$$\lambda_{down} = \frac{Q_{down-outlet}}{Q_{inlet}} \tag{2}$$

Here, $Q_{up\text{-}outlet}$, $Q_{down\text{-}outlet}$, and Q_{inlet} are the flow rate of the up-outlet, down-outlet, and inlet of the T-junction in m^3/h, respectively.

Figure 2 displays the distribution of gas volume fraction in the section of T-junction. The up-outlet flow split ratio is 0.3, and the inlet pressure is 0.2 MPa. It is shown that the gas−liquid separation phenomenon can be simulated by either the Euler model or the mixture model. However, the distribution performs differently between these two models. The gas−liquid separation result of the T-junction, which is calculated by the Euler model, is slightly better than the result of the mixture model. To make a detailed comparison, the gas volume fraction of the two outlets is given in Figure 3. In this figure, the (a) and (c) correspond to the up-outlet and down-

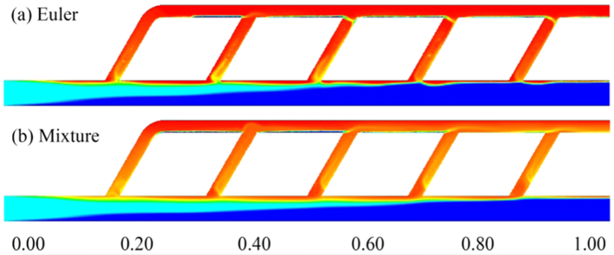


Figure 2. Comparison of the distribution of the value of gas volume fraction between the Euler and mixture models.

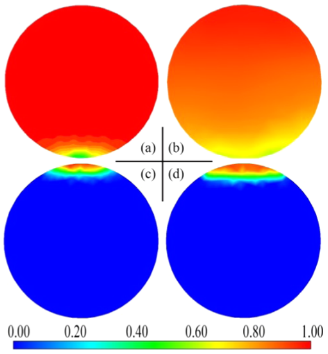


Figure 3. Distribution of the gas volume fraction at the outlets of the T-junction: (a) up-outlet of Euler; (b) up-outlet of mixture; (c) down-outlet of Euler; and (d) down-outlet of the mixture.

outlet of the T-junction, these are calculated using the Euler model, and the gas volume fractions are 0.91 and 0.02, respectively. The (b) and (d) are the up-outlet and down-outlet of the T-junction calculated using the mixture model, where the gas volume fractions are 0.88 and 0.04, respectively.

In the south sea of China, a series of experiments related to gas−liquid flow and separation in the T-junction were done in the petroleum production field. These were carried out to check the accuracy of the simulation results. The structural style and size of the experimental T-junction are the same as the numerical simulation. The physical parameters of gas and liquid which were used in the numerical simulation are used in the experiments. Additionally, the inlet conditions, including velocity, bubble diameter, and phase volume fraction, remain the same between the experiments and the simulation.

The experimental equipment is displayed in Figure 4a. In these experiments, the mixture flow rate and the gas volume fraction were simultaneously measured and sampled using a Coriolis mass flow meter. A single sampling result is shown in Figure 4b,c for the up-outlet and down-outlet of the T-junction, where the up-outlet flow split ratio is 0.3. It is clear that the sample of the up-outlet contains some liquid foam, and the sample of the down-outlet contains some bubbles on the surface. This phenomenon is similar to numerical simulation. The comparison of the phase volume fraction in the outlets of the T-junction between the experimental results and the numerical simulation is given in Figure 5. It shows that the result from the mixture model best fits the field experiments than the Euler model. Therefore, in this study, the mixture model was chosen to be more suitable for calculating the gas−liquid two-phase flow and separation behaviors in the T-junction. As a result, the mixture model was chosen to research the gas−liquid separation characteristics of a T-junction.

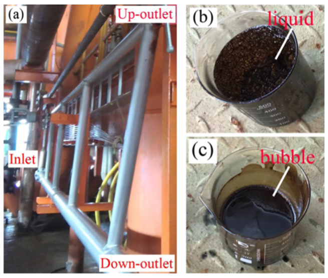


Figure 4. Experimental equipment and the results of the T-junction in the petroleum industrial field: (a) equipment; (b) up-outlet; and (c) down-outlet.

3. RESULTS AND DISCUSSION

In this section, the gas−liquid two-phase separation characteristics in the T-junction are studied by the numerical simulation using the mixture model. Additionally, the crude oil used above was chosen as the liquid phase. A separation efficiency parameter η was introduced to analyze the separation result.[12] It is used to describe the gas−liquid two-phase separation consequence available.

$$\eta = \left| \frac{Q_{\mathrm{g,\ up-outlet}}}{Q_{\mathrm{g,inlet}}} - \frac{Q_{\mathrm{l,\ up-outlet}}}{Q_{\mathrm{l,inlet}}} \right| \times 100\% \tag{3}$$

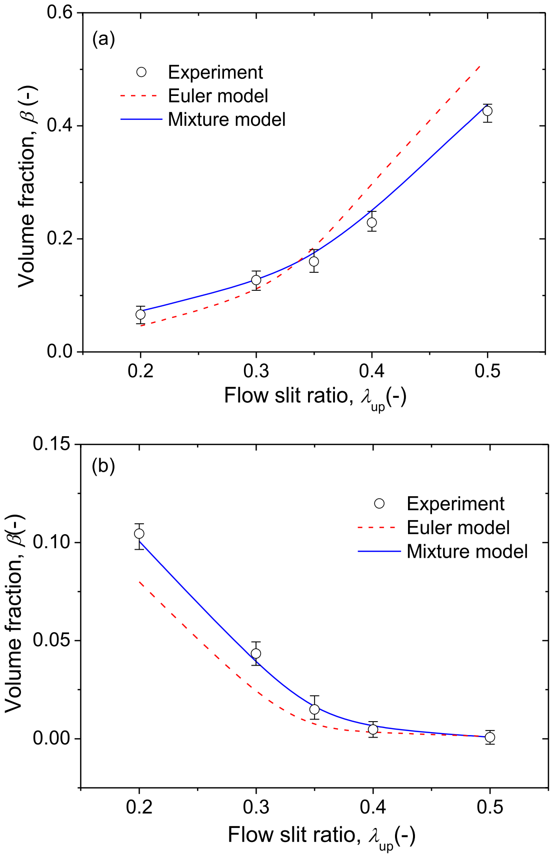


Figure 5. Comparison of the phase volume fraction of the outlets between the experiment and numerical simulations: (a) liquid volume fraction in the up-outlet and (b) gas volume fraction in the down-outlet.

In the equation above, $Q_{\mathrm{g,\ up\text{-}outlet}}$ and $Q_{\mathrm{g,\ inlet}}$ are the gas flow rates in the up-outlet and the inlet of the T-junction (m^3/h). $Q_{\mathrm{l,up\text{-}outlet}}$ and $Q_{\mathrm{l,inlet}}$ are the liquid flow rates in the up-outlet and the inlet of T-junction (m^3/h).

3.1. Effect of the Flow Split Ratio on Separation. The flow split ratios of the two outlets have a significant influence on the gas and liquid phase distribution in the T-junction. As a result, the gas−liquid separation phenomenon is influenced by the different flow split ratios. In this section, a series of up-outlet flow split ratios are designed to study its effect on the gas−liquid two-phase separation consequence. The inlet mixture flow velocity and gas volume fraction were designed as 1.0 m/s and 0.3, respectively. The inlet distribution of the gas and liquid mixture is homogeneous, and the droplet diameter of the inlet dispersed gas is 0.5 mm.

In the result, the distribution of gas volume fraction in the section of the T-junction with different up-outlet flow split ratios of 0.2, 0.3, and 0.5 is displayed in Figure 6. It shows that the phase distribution is remarkably different when the up-outlet flow split ratio changed, as the increasing up-outlet flow split ratio in the upside of T-junction increased, the gas volume fraction decreased and the liquid volume fraction increased. Figure 7 shows the changing behavior of the phase volume fraction in the two outlets as the up-outlet flow split ratio increases. It can be seen that the liquid volume fraction in the up-outlet keeps increasing and the gas volume fraction in the down-outlet keeps decreasing as the up-outlet flow split ratio is increased from 0.2 to 0.5. The gas volume fraction in the

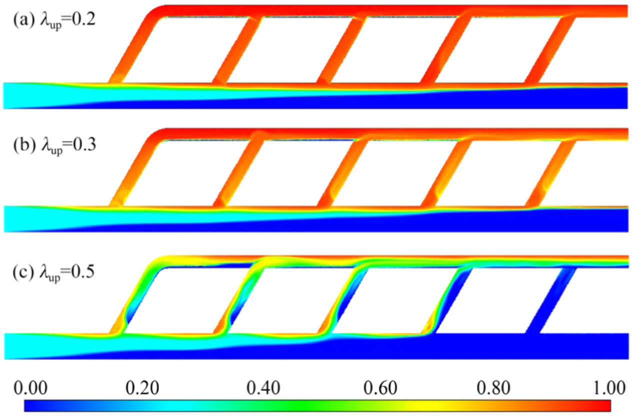


Figure 6. Distribution of gas volume fraction in the section of the T-junction with different flow split ratios.

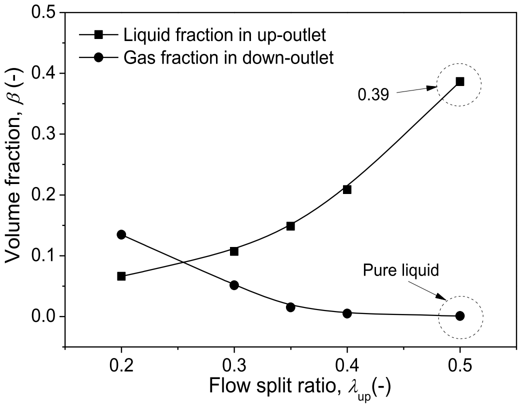


Figure 7. Separation phenomenon in the up-outlet and the down-outlet of the T-junction with different up-outlet flow split ratios.

down-outlet is almost reduced to zero, and the corresponding liquid volume fraction in the up-outlet is 0.39 when the up-outlet flow split ratio is 0.5. In other words, when the up-outlet flow split ratio is higher than 0.5, the flow is pure liquid in the down-outlet.

To evaluate the gas–liquid two-phase separation result in the T-junction, the changing behavior of the separation efficiency when the up-outlet flow split ratio increases is given in Figure 8. It shows that initially the separation efficiency increased when the up-outlet flow split ratio increases, and then it decreased once the up-outlet flow split ratio is higher than 0.39. In summary, the flow split has a great influence on the gas–liquid two-phase separation, and the best flow split ratio of 0.39 exists, where the gas–liquid separation increases to its peak value, which provides a separation efficiency of 94%.

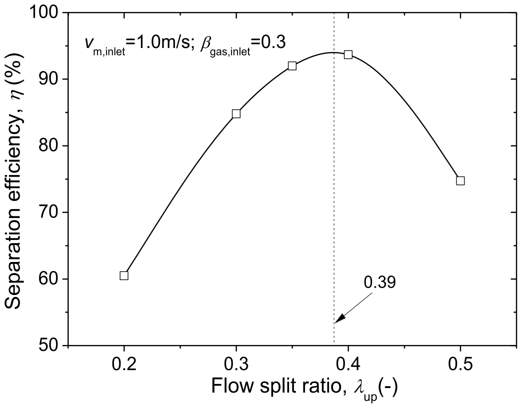


Figure 8. Effect of the up-outlet flow split ratio on the gas–liquid separation efficiency of the T-junction.

3.2. Effect of the Inlet Velocity on Separation. It is quite well established that the flow velocity has a significant influence on the flow pattern of the gas–liquid two-phase flow in a pipeline. In addition, the flow velocity affects the gas–liquid two-phase flow and separation characteristics in a T-junction. In this section, the effect of the inlet gas–liquid mixture velocity on the separation phenomenon is studied to obtain the maximum separated capacity of the T-junction. The inlet gas volume fraction was designed to be 0.3. Also, the up-outlet flow split ratio was fixed at 0.3. The inlet distribution of gas and liquid mixture is homogeneous, and the droplet diameter of the inlet dispersed gas is 0.5 mm.

The distribution of the gas volume fraction in the section of the T-junction with different inlet mixture flow velocities is displayed in Figure 9. It shows that the gas–liquid two-phase separation is worsened as the inlet flow velocity in the T-junction increases. The liquid volume fraction in the up-outlet and the gas volume fraction in the down-outlet were simultaneously increased when the inlet flow velocity was increased.

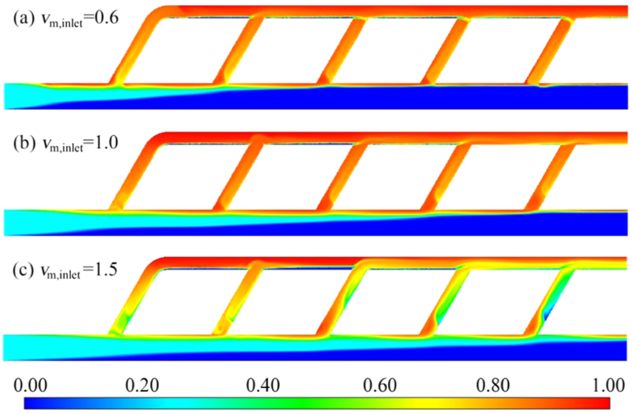


Figure 9. Distribution of the gas volume fraction in the section of the T-junction with different inlet flow velocities.

Figure 10 displays the effect of the inlet mixture velocity on the separation efficiency. It is clear that the separation efficiency keeps decreasing as the inlet velocity increases. When the inlet mixture velocity is 1.0 m/s, the separation efficiency is about 85%; in this condition, the liquid volume fraction in the up-outlet and the gas volume fraction in the down-outlet are 0.11 and 0.05, respectively. However, the separation efficiency decreases to 70% when the inlet velocity increases to 1.5 m/s. This is not feasible for the gas–liquid two-phase separation in a T-junction.

3.3. Effect of the Inlet Bubble Diameter on Separation. In the petroleum industry, due to the flow shearing of valves, elbows, etc. in the pipeline flow, the bubble diameter of a gas–liquid two-phase mixture is fickle. This must have a significant influence on the gas–liquid two-phase separation. Therefore, to obtain the separation ability of the T-junction for different inlet gas–liquid mixtures, the effect of the inlet bubble diameter on the gas–liquid two-phase separation

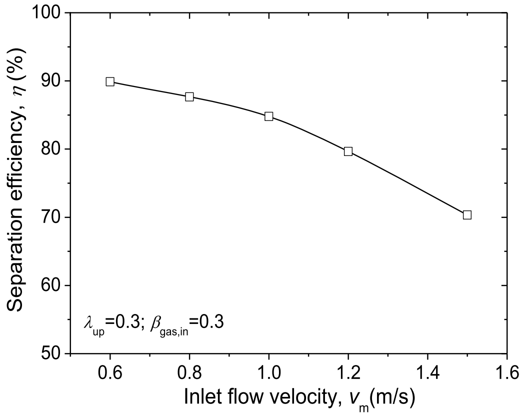


Figure 10. Effect of the inlet flow velocity on the gas−liquid separation efficiency of T-junction.

is researched. The inlet mixture flow velocity and gas volume fraction were designed to be 1.0 m/s and 0.3, respectively. Additionally, the up-outlet flow split ratio was fixed at 0.3.

Figure 11 displays the distribution of gas volume fraction in the section of the T-junction with different inlet bubble diameters of 0.3, 0.8, and 1.4 mm. It shows that as the inlet bubble diameter in the T-junction increases, the gas−liquid two-phase separation improves. Simultaneously, the liquid volume fraction in the up-outlet and the gas volume fraction in the down-outlet are decreased when the inlet bubble diameter increases. Furthermore, in the pipeline flow, it is easier to separate the gas and liquid when the bubble diameter is increased. In Figure 11c, it can be seen that the gas and liquid are separated almost completely when the mixture flows to the third inclined side arms of the T-junction.

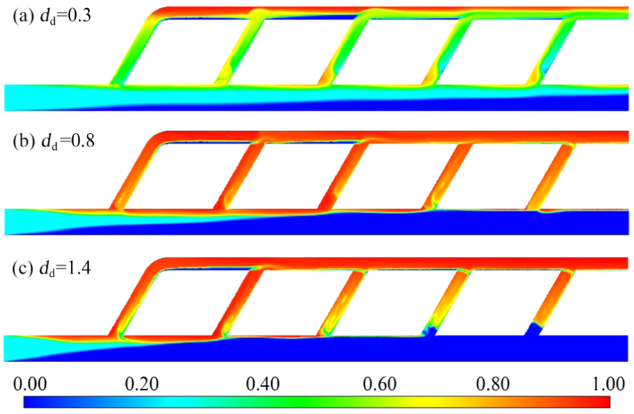


Figure 11. Distribution of the gas volume fraction in the section of the T-junction with different inlet bubble diameters.

Figure 12 shows the changing behavior of the separation efficiency when the inlet bubble diameter is increased. It is clear that the separation efficiency keeps increasing as the inlet bubble diameter is increased. Obviously, the separation efficiency is about 85% when the inlet bubble diameter is 0.5 mm, and, at the corresponding condition, the liquid volume fraction in the up-outlet and the gas volume fraction in the down-outlet are 0.11 and 0.05, respectively. However, the separation efficiency decreases to 54% when the inlet bubble diameter decreases to 0.3 mm, this is unacceptable for good gas−liquid two-phase separation in a T-junction. According to the results, to obtain an efficient gas−liquid two-phase separation, the size of the T-junction should be increased for the small inlet bubble diameter gas−liquid mixtures to increase the standing time in the T-junction.

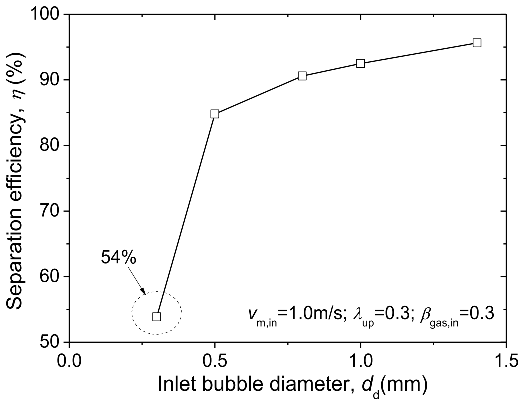


Figure 12. Effect of the inlet dispersed phase diameter on the gas−liquid separation efficiency of the T-junction.

4. CONCLUSIONS

In comparison to the traditional vessel separator, as a separator, the T-junction can decrease the pressure drop and increase the speed of separation. Additionally, the compact size of the T-junction separator is smaller than that of the vessels; this reduces the costs associated with building. In the present study, the gas−liquid two-phase separation characteristics in multiple T-junctions were investigated through a series of numerical simulations and field experiments. Based on the results, it can be stated that the mixture model showed greater potential as the more adaptive multiphase flow model to calculate the gas−liquid two-phase flow and the separation phenomenon in a T-junction when comparing the simulated results with field experimental results. It is useful to design the T-junction as a gas−liquid two-phase separator. Next, the mixture model was used to investigate the gas−liquid two-phase separation behaviors, which included the effect of inlet flow velocity, inlet bubble diameter, and the split ratio of the two outlets.

Initially, the separation efficiency increased when the up-outlet flow split ratio increased, and then it decreased. When the gas−liquid two-phase separation is increased to the best consequence, a best flow split ratio exists, and it changes according to different separation demands of gas or liquid. The flow split ratio is defined as the ratio of the outflow and inlet flow. Hence, the flow meter can be used as the control signal, which can measure the relevant pipeline flow rate accurately during the industrial application of a T-junction. The separation efficiency keeps decreasing as the inlet velocity is increased. So, it is necessary to reduce the inlet mixture velocity to improve the gas−liquid two-phase separation. In other words, the size of the T-junction should be increased to obtain a better separation for the same inlet flow rate. Furthermore, the separation efficiency keeps increasing as the inlet bubble diameter is increased. Accordingly, the size of the T-junction should be increased for efficient separation of the small inlet bubble diameter gas−liquid mixtures. This increases the standing time in the T-junction, which is conducive to obtaining an efficient gas−liquid two-phase separation. In conclusion, the results are important for devising a design methodology for the T-junction as an industrial separator, which is to be used directly in the petroleum and gas production industries, with the previous research studies reviewed in the introduction.

APPENDIX

Numerical Methods and Multiphase Flow Models

Regarding the multiphase flow simulation, the flow models can be divided into two types: the Euler−Lagrange model and the Euler−Euler model.[21] The Euler−Lagrange model is used to calculate the two-phase flow, where one of the phases is dispersed, the volume fraction of the dispersed phase is less than 0.1.[22] The Euler−Euler model is useful for describing the double continuous two-phase flow, and it includes the Euler model, mixture model, VOF model, and other interface capture models.[23,24] In the present study, the gas−liquid two-phase flow does not have a stable continuous interface between gas and liquid, and the dispersed phase exhibits the phenomenon of coalescence and broken.[25] Therefore, the Euler model and mixture model are much more suitable for the calculation of the gas−liquid two-phase flow and separation behaviors in multiple T-junctions.

(a) Euler model

In the Euler model, the governing equations include continuity and momentum equations for each phase that should be solved in the multiphase flow. The behavior pertaining to momentum exchange between gas and liquid is described, and it should be included in the governing equations. In all instances, the description of the momentum exchange is summarized from some experimental results. However, it is difficult to describe the behaviors accurately because, in the two-phase flow, the interaction between gas and liquid is complex.

The continuity equation of the q phase is

$$\frac{\partial}{\partial t}(\alpha_q\rho_q) + \nabla\cdot(\alpha_q\rho_q u_q) = 0 \tag{A.1}$$

In the equation shown above, ρ_q is the density of the q phase, $\mathbf{u}_q$ is the flow velocity of the q phase, and α_q is the volume fraction of the q phase.

$$\sum_{q=1}^{n}\alpha_q = 1 \tag{A.2}$$

The momentum equation of the q phase is

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_q\rho_q u_q) + \nabla\cdot(\alpha_q\rho_q u_q u_q)\\ &\quad = -\alpha_q\nabla P + \nabla\cdot\boldsymbol{\tau}_q + \alpha_q\rho_q g + \sum_{p=1}^{n}(\boldsymbol{R}_{\boldsymbol{pq}} + m_{pq}{}'\boldsymbol{v}_{\boldsymbol{pq}})\\ &\qquad + \alpha_q\rho_q(F_q + \mathbf{F}_{\mathbf{lift},q} + \mathbf{F}_{\mathbf{vm},q})\end{aligned} \tag{A.3}$$

In the equation shown above, $\boldsymbol{R}_{\boldsymbol{pq}}$ is the interfacial force and its value is influenced by the properties of gas and liquid used, $\boldsymbol{v}_{\boldsymbol{pq}}$ is the relative velocity between phase p and q, $m_{pq}{}'$ is the phase exchange between p and q, $\boldsymbol{\tau}_q$ is the pressure strain sensor of the q phase, $\mathbf{F}_{\mathrm{lift}}$ is the lift force due to the different densities of q and p phases, and $\mathbf{F}_{\mathrm{vm}}$ is the virtual mass force.

$$\sum_{p=1}^{n} R_{\mathbf{pq}} = \sum_{p=1}^{n} K_{pq}(v_p - v_q) \tag{A.4}$$

$$K_{pq} = \frac{\alpha_p\rho_p f_{\mathrm{drag}}}{t_p} \tag{A.5}$$

$$\boldsymbol{\tau}_q = \alpha_q\mu_q(\nabla u_q + \nabla u_q{}^{\mathrm{T}}) + \alpha_q\left(\lambda_q - \frac{2}{3}\mu_q\right)\nabla\cdot u_q I \tag{A.6}$$

$$F_{\mathrm{lift}} = -0.5\alpha_q\rho_q|u_q - u_p| \times (\nabla \times u_q) \tag{A.7}$$

$$F_{\mathbf{vm}} = -0.5\alpha_q\rho_q\left(\frac{\mathrm{d}_q u_q}{\mathrm{d}t} - \frac{\mathrm{d}_p u_p}{\mathrm{d}t}\right) \tag{A.8}$$

In addition to the terms mentioned above, in the above equations, μ_q and λ_q are the first and second viscosity coefficients of the q phase, respectively, f_{drag} is the drag coefficient, and t_p is the relaxation time.

(b) Mixture model

In the Mixture model, the two phases are regarded as a single mixture phase, and the governing equation of the mixture is solved. The interfacial phenomenon is neglected, and the slip velocity will be introduced to describe the two-phase flow. The density ρ_{m} and viscosity μ_{m} of the mixture can be calculated as shown below.

$$\rho_{\mathrm{m}} = \sum_{k=1}^{n}\alpha_k\rho_k \tag{A.9}$$

$$\mu_{\mathrm{m}} = \sum_{k=1}^{n}\alpha_k\mu_k \tag{A.10}$$

The continuity equation of the mixture is,

$$\frac{\partial}{\partial t}(\rho_{\mathrm{m}}) + \nabla\cdot(\rho_{\mathrm{m}}u_{\mathbf{m}}) = 0 \tag{A.11}$$

where the velocity of the mixture can be calculated by the average values of each phase.

$$u_{\mathbf{m}} = \frac{\sum_{k=1}^{n}\alpha_k\rho_k u_k}{\rho_{\mathrm{m}}} \tag{A.12}$$

The momentum equation of the mixture is,

$$\begin{aligned}&\frac{\partial}{\partial t}(\rho_{\mathrm{m}}u_{\mathbf{m}}) + \nabla\cdot(\rho_{\mathrm{m}}u_{\mathbf{m}}u_{\mathbf{m}})\\ &\quad = -\nabla P + \nabla\cdot[\mu_{\mathrm{m}}(\nabla u_{\mathbf{m}} + \nabla u_{\mathbf{m}}{}^{\mathbf{T}})] + \rho_{\mathrm{m}}g + F\\ &\qquad + \nabla\cdot\left(\sum_{k=1}^{n}\alpha_k\rho_k u_{\mathbf{dr},k}u_{\mathbf{dr},k}\right)\end{aligned} \tag{A.13}$$

In this equation, $\boldsymbol{F}$ is the body force, $\mathbf{u}_{\mathbf{dr},k}$ is the drift velocity of the phase k.

$$u_{\mathbf{dr},k} = u_k - u_{\mathrm{m}} \tag{A.14}$$

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11972039, 11602014, and 51509235) and the Strategic Priority Research Program of the Chinese Academy of Science (XDB22030101).

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