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Research Article

Experimental Research and Numerical Simulation on Gas-Liquid Separation Performance at High Gas Void Fraction of Helically Coiled Tube Separator

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The industrial removal process of the light hydrocarbon and water from wet natural gas can be simulated in laboratory with the independently designed helically coiled tube gas-liquid separator. Experiment and numerical simulation are combined to analyze the influences of various inlet velocities and gas void fractions on the gas-liquid separation efficiency and pressure-drop between the inlet and outlet of the helically coiled tube. The results show that, at the inlet velocity of 4 m/s to 18 m/s and the gas void fraction of 88% to 97% for the gas-liquid mixture, the gas-liquid separation efficiency increases at the beginning and then decreases with increasing inlet velocity. Afterwards there is another increasing trend again. The gradient of pressure-drop increases slowly and then fast with the increasing inlet velocity. On the other hand, the gas-liquid separation efficiency first increases with the gas void fraction and then shows a decreasing trend while the pressure-drop keeps falling down with the gas void fraction increasing. Above all the optimal operating parameters of the helically coiled tube separator are inlet velocity of 13 m/s and gas void fraction of 93%, and the separation efficiency and pressure-drop are 95.2% and 0.3 MPa, respectively.

1. Introduction

With the rapid growth of energy demand in the world [1], the resources of offshore oil-gas and desert oil-gas have entered the stage of large-scale development [2–4], and the natural gas which could be directly exploited is mainly wet natural gas containing a small amount of solid particles. Wet natural gas (gas void fraction approximately from 90 to 99%) always refers to such kind of gas containing a certain amount of water or light hydrocarbon in petroleum and natural gas industry. In order to meet the process requirements of the pipeline transportation and accuracy measurement, it is necessary to carry out the gas-liquid separation for wet natural gas. However, due to the limitation of site conditions and process equipment, a good gas-liquid separator generally has to meet some characteristics, including small size, high separation efficiency, high processing capacity, and easy maintenance. Due to these characteristics, as a type of new separator, the helically coiled tube gas-liquid separator has obtained high interest in both research and industrial application.

The helically coiled tube gas-liquid separator is one of the new types of separators, which contains the functions of centrifugal separation and gravity separation. As shown in Figure 1, the structure of separator includes gas collection chamber, separation chamber, and liquid collection chamber from top to bottom. When the inlet velocity of wet gas is high, gas-liquid separation performance mainly depends on the larger centrifugal driven force of the helically coiled tube. On the other hand, when the wet gas velocity becomes quite low, the gravity separation plays the lead role on gas-liquid separation performance making up for the lack of the insufficient centrifugal force. The separation performance of

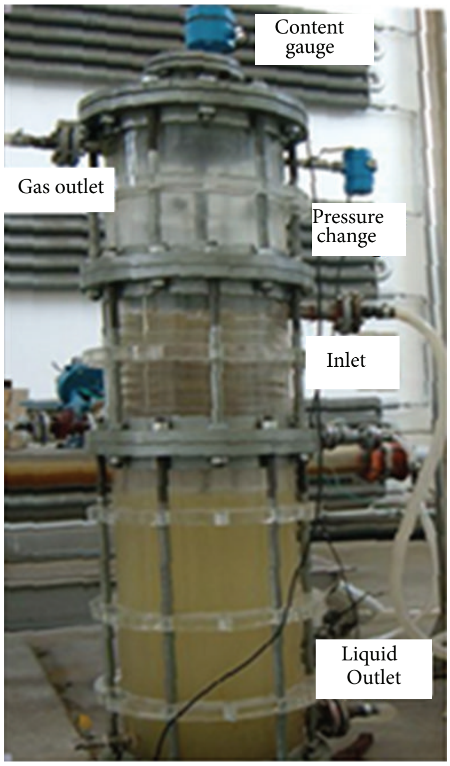

Figure 1: The separator structure.

the independently designed helically coiled tube gas-liquid separator has been studied by experiments and numerical simulation. Experimental studies of oil-gas two-phase flow in the horizontal helically coiled pipes with different diameters have been carried out by Guo et al. [5]. Some research works on phase distribution characteristics of solid-gas-liquid three-phase flow in helical pipes have been made [6, 7]. Gong et al. [8] carried out some researches on the numerical simulation with multiphase flow model and the experiments of oil and water separation. They also proposed the best open position on the wall of helical pipe under low flow rate at the inlet. The separation process of oil-water in helically coiled pipes was studied by Li et al. [9–11]. The focus of this paper is the influence of inlet velocity and gas void fraction on the gas-liquid separation efficiency and pressure-drop between the inlet and outlet of the helically coiled tube. The optimal conditions of the separator are studied and analyzed in this paper.

2. The Experimental Setup

The whole experimental system is mainly composed of atomization system and separation system [12, 13] as shown in Figure 2.

In the atomization system, compressor provides high pressure air and pump transports high pressure liquid water. The high pressure water is atomized into droplet group after nozzle and then injected into the high pressure air. After intensive blend, the gas-liquid mixture enters into the tangential inlet of the separation chamber. Through adjusting the valve, various inlet velocities and gas void fractions of the gas-liquid mixture can be obtained.

As the core of the helically coiled tube gas-liquid separator, the separation system plays the key role in the performance of the separator. Gas-liquid mixture is sent into the entrance of helically coiled tube. After centrifugal separation of the initial circles, air is rapidly discharged into the gas collection chamber along the separation holes inner upside the helical coil tube and water is gathering into the liquid collection chamber. After separation, air is emptied and water is circularly used.

The separator was designed to a cylindrical vertical structure with diameter of 325 mm and the total height of the separator is 1500 mm including the gas collection chamber with height of 300 mm, the separation chamber with height of 400 mm, and liquid collection chamber with height of 800 mm. The diameters of inlet and outlet tube of gas and liquid are both 25 mm [14]. The gas circuit was equipped with a gas flow meter and a pressure-regulating valve. The liquid circuit was equipped with a liquid flow meter and a pressure-regulating valve. The separator was equipped with a liquid level-meter.

3. Experimental Method

The experimental medium was chosen to be the mixture of water and air, whose physical property is quite similar to the wet natural gas such as low volatility at room temperature. Therefore the mixture can be used to approximately simulate the process of removal of the light hydrocarbon, water, and other liquid phase components from the wet natural gas. At the beginning of the experiment, the valve of the gas circuit before being mixed was kept close, but the inlet valve of the separator, the inlet valve of water circuit, the outlet valve of gas circuit, and the outlet valve of water circuit should be open. The pump was started to establish a certain level of water in the liquid collection chamber. After the stability of liquid circuit system reached a stable state, the air compressor was started and then the valve of gas circuit was opened. By adjusting the vent valve in front of the gas flow meter, a proper air flow can be obtained in the gas circuit. After the stabilization of gas-liquid flow, the separation efficiency can be calculated as follows:

$$\eta = \frac{Q_2 t}{Q_1 t}, \tag{1}$$

where Q_1 is the reading number of liquid flow meters at entrance of water circuit, Q_2 is the reading number of liquid flow meters at export of liquid collection chamber, and t is the running time.

4. Result and Analysis

During the experiment, the room temperature and barometric pressure are chosen as the experimental temperature and pressure respectively. During the postprocessing calculation, the density and viscosity of water are $1000\,\text{kg/m}^3$ and 5×10^{-3} Pa·s, respectively while those of the air are $1.237\,\text{kg/m}^3$

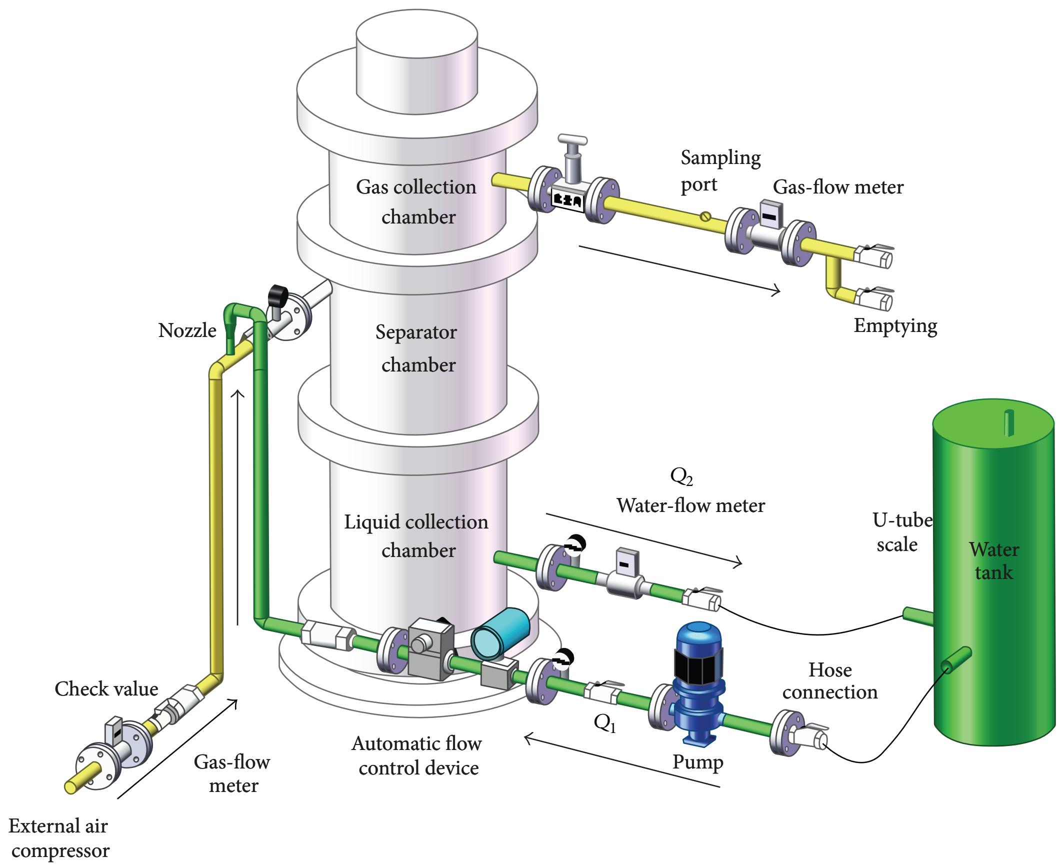

Figure 2: The system diagram of the experiment setup.

and 1.822×10^{-5} Pa·s, respectively. The experiment is mainly concerned with the separation efficiency and pressure-drop which can well reflect the separation performance under different inlet velocities and gas void fractions. The total of 76 conditions can be separated into two parts: one part is at the inlet velocities of 5 m/s, 8 m/s, 10 m/s, 13 m/s, 14 m/s, 15 m/s, 16 m/s, 17 m/s, and 18 m/s under the gas void fractions of 90%, 93%, 95%, and 97% and the other is under the gas void fractions of 88%, 89%, 90%, 91%, 92%, 93%, 94%, 95%, 96%, and 97% at the inlet velocities of 5 m/s, 10 m/s, 13 m/s, and 18 m/s.

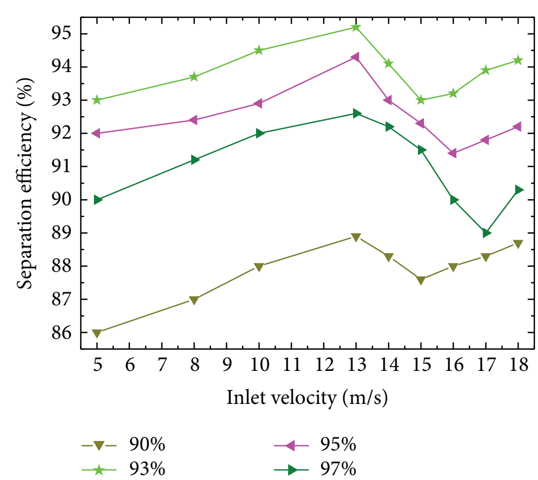

Figure 3: The influence of the inlet velocity on separation efficiency under different gas void fractions.

4.1. The Influence of Inlet Velocity on Separation Performance. Figure 3 represents the influence of the inlet velocity on separation efficiency under different gas void fractions. It can be seen that, at a constant gas void fraction for the gas-liquid mixture, the gas-liquid separation efficiency increases with inlet velocity in the range of 5 to 18 m/s. At an inlet velocity of 13 m/s and a gas void fraction of 93%, the separation efficiency reaches the peak value of 95.2%. With the inlet velocity further increasing, the separation efficiency decreases at first and then increases again. The phenomenon is reasonable because the centrifugal force is enhanced with the increasing of inlet velocity leading to better gas-liquid separation efficiency. However, along with the inlet velocity further increasing, large numbers of droplets start to break up before separation from the gas flow due to the anabatic shear force. Meanwhile the stay time is shortened for the mixture in the helical coil pipe resulting in the increase of pressure-drop and energy consumption.

Figure 4 shows the influence of the inlet velocity on pressure-drop between the inlet and outlet of the helical coil

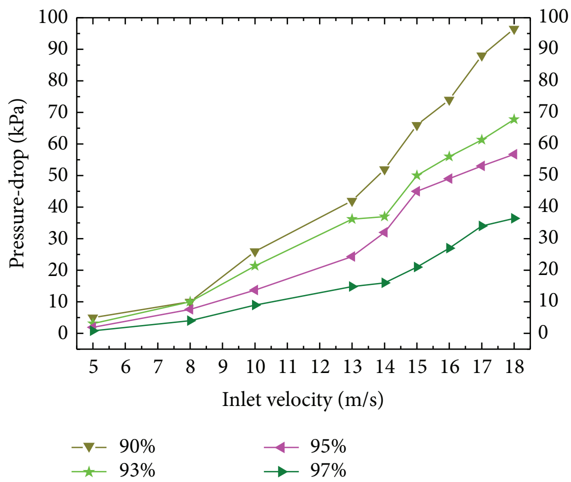

Figure 4: The influence of the inlet velocity on pressure-drop under different gas void fractions.

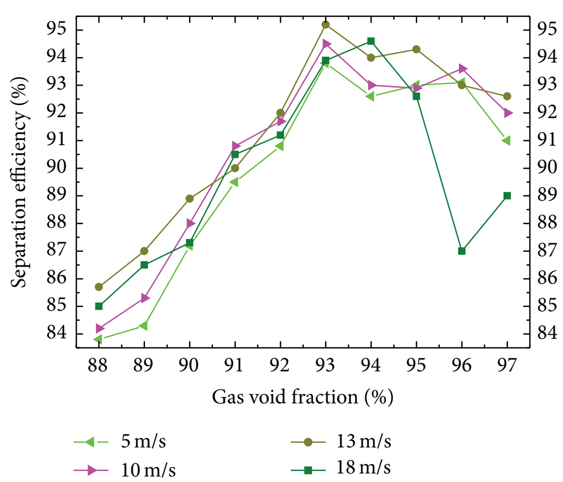

Figure 5: The influence of gas void fraction on the separation efficiency under different inlet velocities.

tube under different gas void fractions. It can be seen that, at a constant gas void fraction for the gas-liquid mixture, the pressure-drop increases with the inlet velocity in the range of 5 to 18 m/s. At the range of 5 to 14 m/s the pressure-drop rises slowly and then it becomes fast at the range of 14 to 18 m/s, which shows a good manner of quadratic behavior for the transition of pressure drop. The reason can be explained by the fact that the increasing of inlet velocity results in much more flow loss. But with the inlet velocity further increasing, the local loss is rapidly increased resulting in the larger pressure-drop.

4.2. The Influence of Gas Void Fraction on Separation Performance. Figure 5 is the influence of gas void fraction on the separation efficiency under different inlet velocities. It can be seen that, at a constant inlet velocity for the gas-liquid mixture, the gas-liquid separation efficiency first increases and then decreases with gas void fraction in the range of

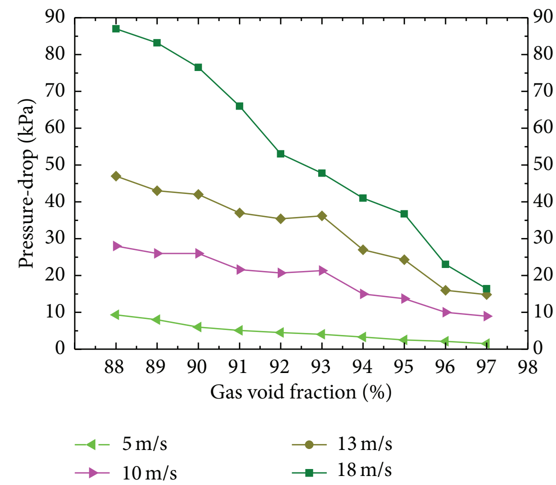

Figure 6: The influence of gas void fraction on the pressure-drop under different inlet velocities.

88% to 97%. When gas void fraction is at the range of 93% to 94%, the separation efficiency reaches the peak under different inlet velocities. This is mainly because a bigger gas void fraction can promote the droplet to assemble at the outside of the helical coil tube and forms a continuous gas zone at the inner side, which improves the separation effect. However, with gas void fraction further increasing, the gas phase zone would become intermittent and the flow pattern turns to be mist flow [15]. The flow field becomes unstable and easy-disturbing and consequently the continuous gas blows away the water and makes the water droplet or water mist suspended in the high speed gas stream. So the water droplet is taken away with the discharge of air via holes resulting in bad separation effect.

Figure 6 shows that, at a constant inlet velocity, the pressure-drop decreases with the gas void fraction in the range of 88% to 97%. This is mainly because, with the gas void fraction increasing, the viscosity of the gas-liquid mixture decreases and the wall shear forces lower resulting in the fall of the pressure-drop.

Taking the above results into comprehensive consideration as well as the separation efficiency and the pressure-drop of the helically coiled tube gas-liquid separator, the separator has an ideal operating condition point, which is the fact that the inlet velocity and the gas void fraction are 13 m/s and 93%, respectively, and at this condition the separation efficiency reaches 95.2% and the pressure-drop is 0.3 MPa.

5. Numerical Simulation

The gas-liquid separation performance of the helically coiled tube separator with holes is influenced by coupling multi-parameters such as inlet velocity, gas void fraction, gas and liquid physical properties, turning radius, pitch, diameter of tube, number of helical turns, and the size of holes [16]. It is impractical for experiment alone to study and optimize these parameters one by one due to huge workload, and more because of the coupling nonlinear of these parameters on the

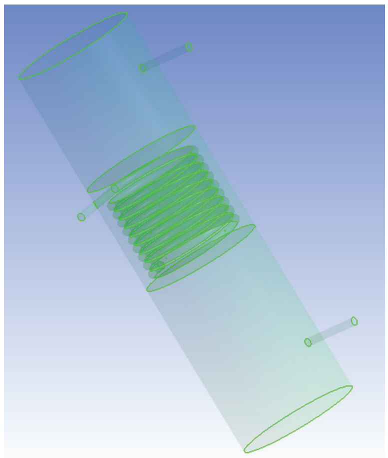

Figure 7: The 3D model of the separator.

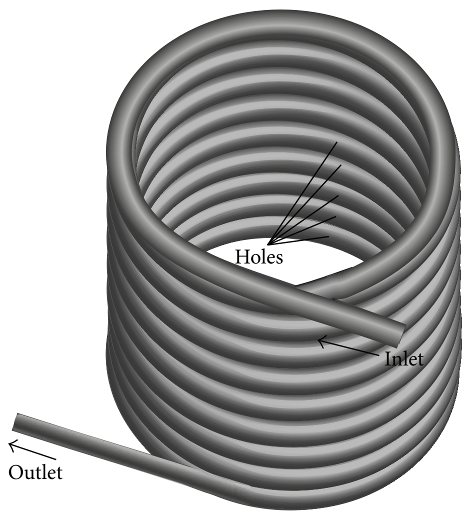

Figure 8: The helical coil tube with holes.

separation effect single optimal parameter combination is not really the optimal condition point. Therefore, it is necessary to use the advantages of experimental research and numerical simulation. Through comparative analysis with numerical and experimental results, the use of reliable numerical models to research on gas-liquid separation performance of helically coiled separator is more systematic and in-depth which has a certain guiding significance in the future.

5.1. Meshing and Models. The 3D models of the separator were produced by professional software Ansys DM as shown in Figure 7. In order to reduce the effect of boundary condition on inner flow, the inlet and outlet were extended. The calculation domains were meshed and checked by software Ansys Meshing. Due to the complexity of the helically coiled tube geometry the unstructured tetrahedral and local refinement were used. The quality of the whole mesh was checked less than 0.7 while the number closing to zero represents the best mesh quality in Meshing code, which proved that the grid was good.

Ansys Fluent software was adopted to simulate the inner flow field by assuming that the fluid is steady, viscous, and incompressible [17]. The RNG k-ε turbulent model and multiphase flow Euler model are applied to close the RANS equations with SIMPLE [18–21] algorithm to solve. It is considered that the calculation is over when the calculation residual is less than 0.001.

The velocity inlet with a certain gas void fraction and outflow were selected as inlet and outlet boundary conditions assuming that the inlet velocity u_{in} is distributed uniformly at axis direction. The 19 outflow holes of tube are set at the pressure outlet condition. The turbulent condition at pump inlet can be described by turbulent kinetic k_{in} and turbulent dissipation rate ε_{in} as follows:

$$\begin{aligned} u_{\text{in}} &= \frac{4Q}{\left(3.14 \times D_{\text{in}}^2\right)}, \\ k_{\text{in}} &= 0.005 u_{\text{in}}^2, \\ \varepsilon_{\text{in}} &= \frac{\left(C_\mu^{0.75} k_{\text{in}}^{1.5}\right)}{l}, \end{aligned} \tag{2}$$

where Q is the flow rate of the gas-liquid mixture, D_{in} is the diameter of the helically coiled tube, l is the turbulent length scale, $l = 0.07 D_{\text{in}}$, and $C_\mu = 0.09$.

As to wall boundary condition, no slip condition is enforced on wall surface and standard wall function is applied to adjacent region.

The helical tube adopts the basic size with gyration radius of 150 mm, 9 laps, and tube diameter of 25 mm and pitch of 25 mm. The top of helical tube is entrance and the bottom is export. A certain extent in the inlet and outlet reduces the disturbing from reflux on the inner flow field. From the fifth lap the helical coil tube opens the holes uniformly distributed in every 90° around each lap with the diameter of 3 mm and location inside the helical tube upper 3° from the horizontal center. The internal of every two holes with length of a quarter circle of helical pipe without holes is considered as "adjustment segment," facilitating better stratified flow and steady flow as shown in Figure 8.

The grid independence and sensitivity in the simulation have been investigated. Two physical quantities such as efficiency and pressure-drop are chosen as the evaluation parameters for the effect of mesh size on the final solution as shown in Table 1. Then Mesh 3 is employed for the next calculation in order to reduce the calculation loads and guarantee the calculation accuracy. When the effect of grid number on separation performance is less than 1%, the mesh is available. The grid number of the whole structure reaches 4.17 million. Figure 9 gives the meshing of helically coiled tube separator.

5.2. The Influence of Inlet Velocity and Gas Void Fraction on Separation Performance of the Helical Tube Gas-Liquid Separator. The influence of inlet velocity on separation performance has been drawn in Figures 10 and 11. It can be seen that, at a constant gas void fraction, the inlet velocity ranging from 5 m/s to 13 m/s increases the separation efficiency and

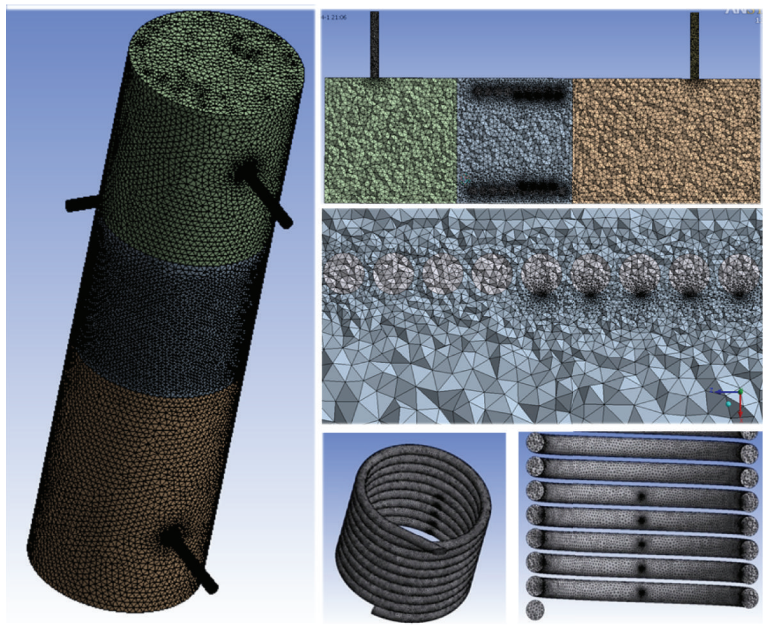

Figure 9: The meshing of helically coiled tube separator.

Table 1: Evaluation of the dependency of mesh.

Items	Mesh 1	Mesh 2	Mesh 3	Mesh 4
Total grid	3489397	3951551	4176194	4527358
η/η_3	0.998249	1.001912	1.0	1.000697
$\Delta P/\Delta P_3$	0.998061	1.002053	1.0	1.00767

improves the flow condition. And at 13 m/s the separation efficiency reaches the peak value 89.3% under the gas void fraction of 93%. With the inlet velocity further increasing from 13 m/s to 18 m/s, the separation efficiency decreases at first and then increases slowly again. Meanwhile at the range of 5 to 14 m/s the pressure-drop rises slowly and then it becomes fast at the range of 14 to 18 m/s with the same regularity to the experiment.

Figures 12 and 13 perform the influence of gas void fraction on separation performance. It can be seen that, at a constant inlet velocity for the gas-liquid mixture, the gas-liquid separation efficiency increases with gas void fraction firstly in the range of 90% to 93%. And at a gas void fraction of 93% and an inlet velocity of 13 m/s, the separation efficiency reaches a peak value of 89.3%. When the gas void fraction changes from 93% to 97%, the separation efficiency shows a downward trend. At the same time, the pressure-drop also decreases with gas void fraction increasing.

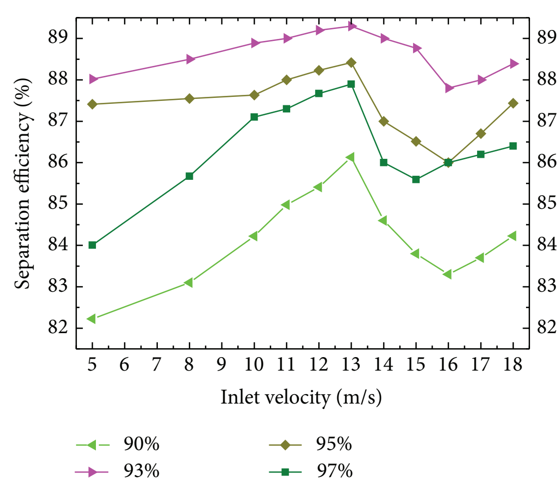

Figure 10: The influence of inlet velocity on separation efficiency.

5.3. The Flow Field on Holes Section of the Helically Coiled Tube Gas-Liquid Separator. Figure 14 shows the flow field and contour of gas void fraction at holes section of the 5~9 helically coiled tube laps with the inlet velocity of 13 m/s and gas void fraction of 90%. The upper and the lower rows represent the first and the last sections of the hole, respectively, in each lap. The oriented lines in each section are the projection component of spatial streamline on each section. From the contour of the gas void fraction it can be seen that the air gathers in the inner side of helically coiled tube and the water concentrates on outside under the combined actions of the gravity and the centrifugal forces. The separation effect has been strengthened after each helically coiled tube lap. In the first five laps the separation effect basically reaches the limit and there will be no significant improvement. Compare the

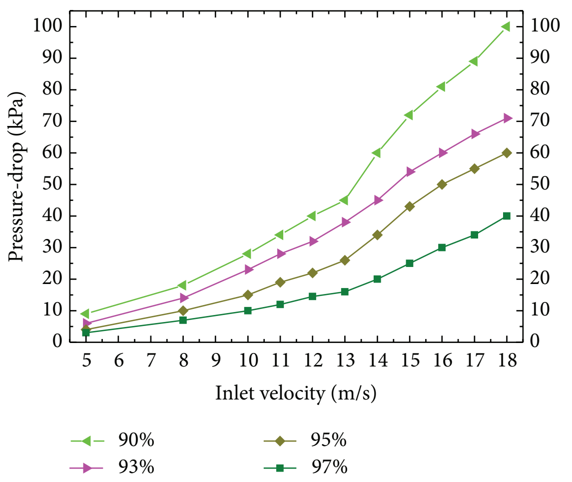

FIGURE 11: The influence of inlet velocity on pressure-drop.

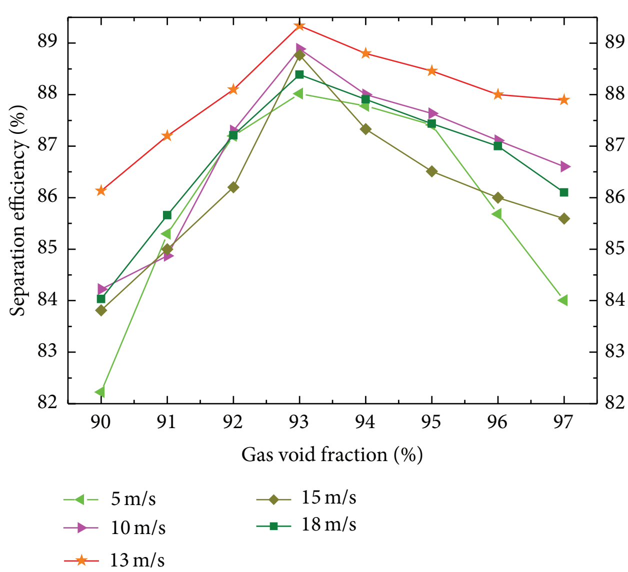

FIGURE 12: The influence of gas void fraction on separation efficiency.

first and the last hole section in each lap, it is obvious to find that each outflow of gas flow at holes disturbs the whole inner flow field of the helically coiled tube and weakens the liquid layered effect, leading to less outflow for high gas void fraction gas and this effect will be cumulative to the maximum for the last one outflow hole of each lap. The spacing between holes can be regarded as "adjustment segment." By increasing the spacing, the mixture of stratified flow with bad separation effect gets fully adjusted to deteriorate, to recover, and further to improve the separation efficiency [22].

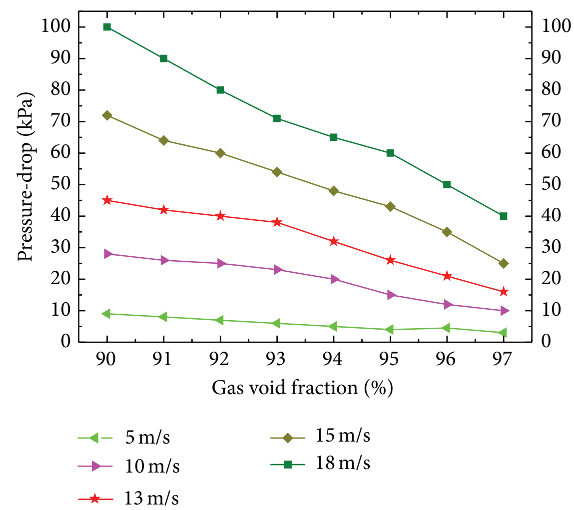

FIGURE 13: The influence of gas void fraction on pressure-drop.

6. Comparison with the Experimental Data and Numerical Result

In order to verify the reliability of the selected models, five conditions at inlet velocities of 5 m/s, 10 m/s, 13 m/s, 15 m/s, and 18 m/s are chosen to make comparison.

6.1. The Comparison of Separation Efficiency. The experimental and numerical separation efficiency of the helically coiled tube separator with gas void fraction are compared in Figure 15 under several inlet velocity points of 5 m/s, 10 m/s, 13 m/s, 15 m/s, and 18 m/s. From Figure 15 it can be known that the experimental data and numerical result have the same regularity trend, and the numerical value is lower. This is because the boundary conditions set in simulations are different with the actual experimental conditions, such as the droplet diameter of 0.1 mm and the bubble diameter of 1 mm. However in the actual experiment, the two-phase particles are deformed at all times. What is more, the gas-liquid flow rate may not be very accurate during the experiment. The inlet and outlet of the separator are equipped with valves which influence the inlet velocity of gas-liquid two-phase and the degree of mixing. Meanwhile, the process parameters are also affected by air temperature, humidity, and other factors. These above all are the reasons leading to the difference of the separation efficiency.

6.2. The Comparison of Pressure-Drop. The experimental and numerical pressure-drop of the helically coiled tube with gas void fraction are compared in Figure 16 under several inlet velocity points of 5 m/s, 10 m/s, 13 m/s, 15 m/s, and 18 m/s. From Figure 16 it can be seen that the experimental data and numerical result share the same trend, and the numerical value is higher. This is mainly because the simulations are performed in an ideal state that the holes at inner side of the helically coiled tube and the outlet of the tube are set at the same pressure condition while it is not the same as the experiment. In addition the separator entrance is connected

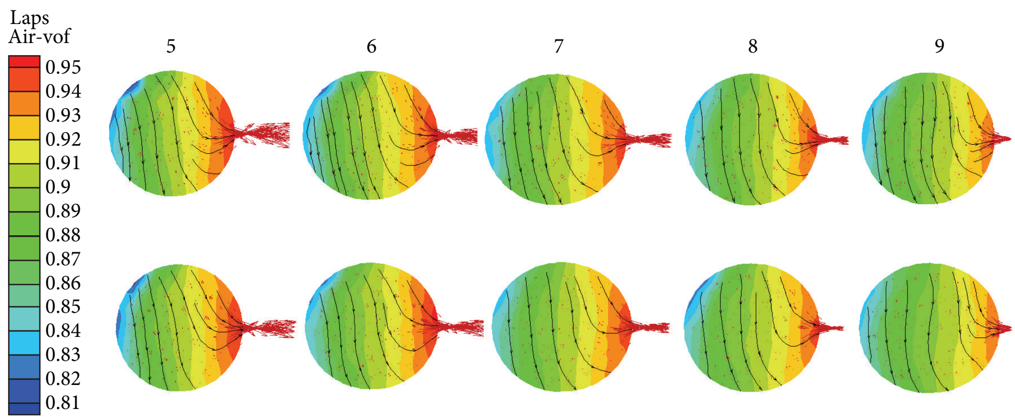

Figure 14: The flow field and contour of gas void fraction on different sections at laps.

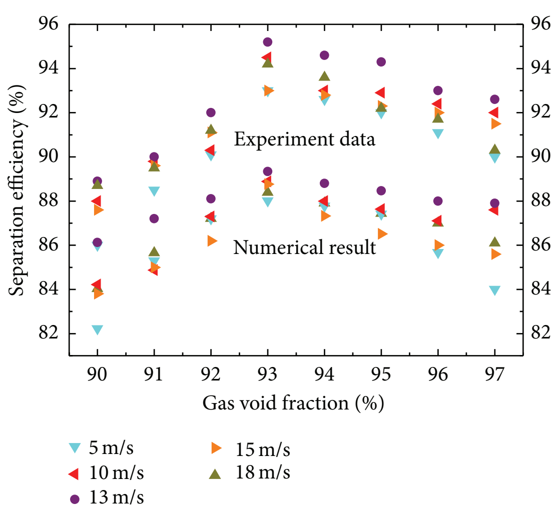

Figure 15: The comparison of separation efficiency between experiment data and numerical result under different velocities.

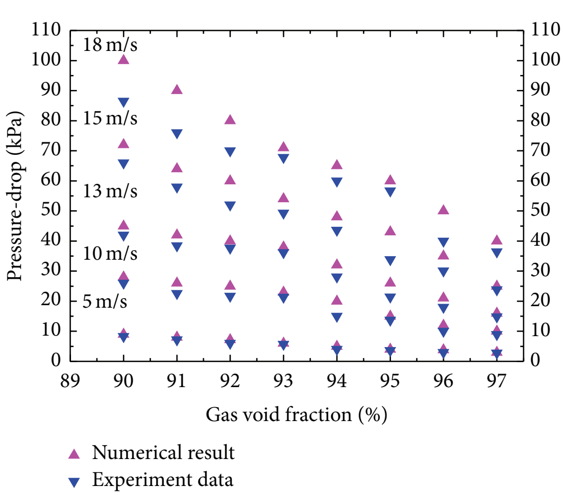

Figure 16: The comparison of pressure-drop between experiment data and numerical result under different velocities.

with a certain distance of pipeline and nozzle during the experiments which have led to the deviation between the experimental data and numerical result.

After larger numbers of data comparisons and verifications, the difference between numerical and experimental results is within the allowable range, and thus the numerical models of the helically coiled tube separator are reliable which can be used for more conditions in the future research.

7. Conclusions

(1) At a constant gas void fraction of the gas-liquid mixture, the gas-liquid separation efficiency increases with the inlet velocity in the range of 5 to 13 m/s. At an inlet velocity of 13 m/s, the separation efficiency reaches the peak value. If the inlet velocity further increases, the separation efficiency decreases first and increases again. Meanwhile, the pressure-drop shows a manner of quadratic behavior with the inlet velocity in the range of 5 to 18 m/s.

(2) At a constant inlet velocity of the gas-liquid mixture, the gas-liquid separation efficiency increases with the gas void fraction in the range of 88 to 97%. At the gas void fraction of 93 to 94%, the separation efficiency reaches the peak value. And with the gas void fraction further increasing, the separation efficiency decreases. Meanwhile the pressure-drop decreases with the inlet velocity increasing.

(3) From the comparison analysis of the separator efficiency and the pressure-drop between the numerical and experimental results it can be seen that both show the same regularity trend and the average deviation is within the allowable range of 11%, which verifies the reliability of the numerical models. Above all, the optimal operating parameters of the helically coiled tube separator are inlet velocity of 13 m/s and gas void fraction of 93% and the separation efficiency and pressure-drop are 95.2% and 0.3 MPa, respectively.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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