

Article

Performance of a Parametrically Optimized T-Junction for Gas–Liquid Separation and Slug Suppression Under Various Flow Patterns

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Abstract

Variations and unstable characteristics of two-phase flow in oil and gas pipelines readily induce severe equipment vibration and internal liquid sloshing, which seriously endanger the safety of pipeline systems. Existing investigations on conventional T-junctions have been restricted to single working conditions, without systematic optimization of structural parameters across multiple flow regimes or full evaluation of integrated separation and slug suppression performance. To address this research gap, this work proposed an optimized four-branch T-junction. The geometric configuration of the T-junction was optimized, and a test prototype was fabricated for gas–liquid two-phase flow experiments. Combined with experimental measurements and computational fluid dynamics (CFD) simulations, the overall performance of the optimized T-junction was comprehensively analyzed under diverse flow patterns and operating conditions. The test results indicated that the gas separation efficiency exceeded 90% under stratified flow, whereas slug flow brought strongly time-dependent separation performance. The gas separation efficiency was maintained above 40% for all test cases. The optimized structure reduced liquid slug velocity and length and significantly suppressed liquid level fluctuations in the downstream separation tank. The numerical predictions agreed well with experimental data, which validated the reliability of the present numerical framework. This study provides technical references for the design of inline pipe separators that realize both gas–liquid separation and slug mitigation.

Keywords: gas–liquid two-phase flow; gas–liquid separation; slug flow; slug suppression; flow patterns



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1. Introduction

Gas–liquid two-phase flow is widely encountered in industrial sectors including petroleum exploitation, chemical production and long-distance pipeline transportation [1–3]. Different matching relationships between gas and liquid flow rates, as well as varying pipeline layouts, will generate diverse flow patterns [4]. Slug flow ranks among the most prevalent flow regimes in such systems, and it imposes severe damage on pipeline infrastructure and matched process equipment [5–7]. Compared with single-phase flow, gas–liquid two-phase flow has more complex flow characteristics and reduces the operational safety margin of industrial facilities. In slug flow, liquid slugs and gas bubbles move alternately, imposing periodic impact forces, severe pressure fluctuations and liquid-level

oscillations on downstream equipment. Long-term cyclic impact will trigger structural vibration and component fatigue, and in extreme cases, lead to equipment failure, which seriously threatens the secure and stable operation of the entire production system.

Gas–liquid separation serves as an effective technical route to suppress violent transient fluctuations induced by instantaneous phase holdup changes, by splitting mixed two-phase fluid into gas-dominated and liquid-dominated streams. For this reason, pipe-type separation devices have attracted extensive research attention in recent years [8,9]. Distinct from bulky traditional separation vessels, such devices achieve gas–liquid phase separation merely through rational layout of standard pipelines, featuring a compact footprint, a simple structure and low manufacturing costs [10]. Physical separation methods relying on gravity or centrifugal force are widely adopted for inline pipeline separation, which enables phase separation while the fluid flows continuously. Gravity separation takes advantage of the high stratification efficiency inside small-diameter pipelines to realize in-pipe phase separation relying solely on gravity. Centrifugal separation generates swirling flow via active or passive structures and accelerates separation by centrifugal force far larger than that of gravity. Typical equipment includes various cyclones and gas–liquid cylindrical cyclones (GLCC).

When gas–liquid two-phase flow passes through a T-junction, spontaneous gas–liquid separation occurs under the combined effects of inertial force, gravity and interfacial force. Nevertheless, uneven phase distribution and asymmetric flow division are prone to emerge inside the tee structure [11,12]. Benefiting from convenient installation and flexible operation, T-junctions have been gradually applied in various engineering scenarios to achieve on-site gas–liquid separation and flow regulation. However, pipe-mounted separation devices have inherent limitations. The flow patterns of gas–liquid two-phase flow vary drastically with operating conditions, while the flow rate and gas–liquid ratio fluctuate continuously throughout the service life of pipelines. Accordingly, the structural design of pipe separators must fully accommodate complex and variable inlet flow conditions to guarantee stable separation performance and flow control capacity across diverse flow regimes.

Due to density and inertial force differences between gas and liquid phases, the mixed fluid undergoes flow and phase redistribution in branch pipes, achieving gas–liquid separation. Numerous researchers have conducted extensive experimental tests and mechanistic analyses on the structural parameters of T-junctions, mainly including the dimensions of branch pipes and main pipes as well as tee types. Relevant studies cover various flow patterns such as stratified wavy flow, slug flow and annular flow [13,14]. Pipe diameter ratio is a core geometric parameter dominating phase splitting performance of T-junctions. A large number of laboratory tests adopting air–water and other working fluids have proved that reducing diameter ratio can cut down interphase entrainment inside branches and improve separation efficiency, yet it will simultaneously raise local pipeline pressure drop and reduce total separated flow capacity [15–17]. Hence, pipe diameter parameters should be determined by comprehensively considering separation performance requirements [18]. Inclination angle is another important parameter of T-junctions, which includes the angle between branch pipes and main pipes, the angle between branch pipes and the horizontal plane, as well as the inclination of upper and lower pipelines relative to the horizontal plane. Calculation results indicate that the influence of branch pipe inclination angle on separation efficiency becomes negligible when the angle exceeds 30° [19].

In the research field of multi-branch T-junctions, existing studies have discussed the effects of branch quantity and inter-branch spacing. The number of flow branches is a key factor affecting pipeline friction loss, liquid accumulation and gas–liquid maldistribution during flow splitting. Relevant experiments have adopted 2–6 branch structures and drawn

differentiated conclusions. With fewer branches, the axial flow path is shorter, and the superposition effect of flow disturbance as gas–liquid two-phase flow passes through the T-junction becomes weaker, leading to a relatively poor liquid separation performance at the downstream pipeline section. In contrast, when 5 or 6 branches are adopted for fluid transportation, the pressure continuously declines along the pipeline. Liquid phases such as oil and water tend to stagnate in the end channels and form liquid holdup sections, while the gas phase preferentially converges into the upstream branches via multiple branch passages [20–22]. For operating conditions including slug flow, branch spacing serves as a critical geometric parameter to adjust the gas–liquid stratification behavior and separation space between neighboring branches. At an extremely small branch spacing (twice the pipe inner diameter, as reported in the existing literature), upstream liquid films and gas slugs flow into downstream branches before complete stratification, resulting in the worst separation efficiency. A moderate spacing of 5–10 pipe diameters provides sufficient space for gas–liquid stratification driven by gravity and interfacial tension. Uniform gas and liquid distribution among all branches can be maintained under various production parameters across a wide range of liquid throughput and gas–liquid ratios. At excessively large branch spacing, the ability of horizontal pipelines to form stratified gas–liquid flow at a given flow velocity declines. Longer horizontal sections are therefore required to reduce inertial effects and achieve effective gas–liquid splitting via branch pipes [23].

T-junctions with different structures present distinct gas–liquid separation performance. The configuration with horizontal main pipes and vertical branch pipes can achieve efficient gas–liquid separation relying on sudden flow channel changes and gravity. Models established based on mass and momentum balance can accurately predict the variations in internal pressure drop and void fraction inside T-junctions, providing theoretical guidance for structural design [24]. Severe slug flow generated inside oil and gas pipelines poses great hazards to pipeline systems and readily triggers intense pressure pulsations and pipeline vibration. T-junctions can break up liquid slugs and reconstruct the flow field to realize slug suppression. Experimental results indicate that during flow splitting in horizontal equal-diameter T-junctions, liquid slugs mainly travel towards the straight-through main pipe under inertial effect, while liquid films attached to the pipe wall tend to enter branch pipes. Throttling structures such as valves and variable-diameter sections alter phase distribution and further affect the evolution and attenuation characteristics of slugs [25,26].

Despite abundant investigations into single parameters and single-flow performance of T-junctions, obvious research gaps remain to be filled. To the best of the authors' knowledge, prior research lacks systematic multi-parameter collaborative optimization for multi-branch inclined T-junctions, and few works comprehensively evaluate their dual performance of gas–liquid separation and slug suppression under stratified flow, slug flow and high-gas-fraction flow simultaneously. Most of the existing literature only conducts tests under a single flow regime or optimizes one geometric parameter independently, without proposing a unified optimal configuration adaptable to variable inlet conditions. Against the above research deficiencies, this paper proposes an optimized multi-branch T-junction configuration after multi-dimensional parametric analysis to confirm the final geometric scheme. The experimental prototype was designed and corresponding CFD models were established based on this optimized structure. Meanwhile, the experimental test system was constructed and numerical calculation parameters were defined. The gas–liquid separation characteristics and liquid level fluctuations in the downstream separation tank were investigated under various gas–liquid ratios and inlet mixture velocities, and the slug suppression performance was analyzed via the flow rates at the inlet and outlets of the T-junction as well as pressure fluctuation signals. The research on the multi-flow

adaptable T-junction with integrated separation and slug attenuation functions can provide technical references for structural optimization and industrial popularization of inline pipe separation equipment in separation engineering.

2. Materials and Methods

2.1. Study on T-Junction Structure

T-junctions can be categorized into various structural forms from different classification perspectives. The T-junction configuration adopted in this study is defined as follows. The device is configured with one inlet and two outlets. The multiphase mixture is introduced through the inlet. Generally, the upper outlet is designed to discharge the light phase, while the separated heavy phase is delivered via the lower outlet. The pipeline coaxial with the inlet is defined as the main pipe, and the pipelines that branch off from the main pipe are termed branch pipes. Multiple branch pipes converge and connect to another outlet pipe.

The diameter ratio, defined as the ratio of the inner diameter of the branch pipe (D_2) to that of the main pipe (D_1), is a fundamental geometric parameter that governs the local pressure loss and two-phase separation performance of T-junctions. Its influence mechanisms vary significantly with fluid types and pipeline layouts. Numerical investigations on gas–liquid two-phase flow reveal that a reduced diameter ratio narrows the flow cross-section and intensifies fluid collision and shear effects at the pipe junction, which inevitably increases the local pressure drop. Meanwhile, it amplifies the diversion discrepancy between gas and liquid phases and improves gas separation efficiency. T-junctions with vertical branch pipes generally exhibit superior gas–liquid separation performance compared with other configurations, and the optimal diameter ratio is strongly dependent on the inlet flow pattern. In practical engineering applications, equal-diameter T-junctions are the preferred structural form.

The angle θ between branch pipes and the main pipe is another critical geometric parameter, which substantially alters the fluid impact position, vortex evolution, flow mixing characteristics and phase separation mechanism. Relevant experimental tests and large eddy simulation have investigated the performance characteristics of T-junctions with different inclination angles. For a 90° T-junction, the fluid impact point is located close to the junction region, making it suitable for conventional flow diversion conditions. When the angle exceeds 30° , its influence on gas–liquid separation performance declines remarkably. Accordingly, the 90° T-junction is widely employed in engineering practice due to its convenient fabrication and assembly.

Due to the relative velocity between the gas and liquid phases in gas–liquid two-phase flow, the drift-flux model was proposed to calculate the void fraction and liquid holdup of two-phase flow [27], which enables more accurate characterization of two-phase flow behaviors. The model is expressed as:

$$v_g = C_0 v_m + v_d, \quad (1)$$

where v_g denotes the actual gas velocity, C_0 is the distribution parameter, v_m is the mixture velocity, and v_d denotes the gas drift velocity. The relationship between v_g and the superficial gas velocity v_{sg} is written as:

$$v_{sg} = \alpha_g (C_0 v_m + v_d), \quad (2)$$

Accordingly, v_d is a function of void fraction α_g , which characterizes the local relative velocity between the gas and liquid phases. The distribution parameter and the calculation formula for gas drift velocity differ across various flow regimes. Numerous studies have

carried out experimental fitting and theoretical derivations, verifying that the superficial gas velocity maintains a linear correlation with the mixture velocity under most flow patterns. Extensive engineering practices and experimental investigations have demonstrated that a downward-inclined pipe downstream is beneficial to gas–liquid separation. By exploiting the density difference between the gas and liquid phases, faster gravity-driven separation can be achieved, during which bubbles acquire higher drift velocities in the flow. For a given flow pattern or void fraction, the superiority or inferiority of pipe inclination on gas–liquid separation can be evaluated by comparing the bubble velocity and gas drift velocity in pipes with different inclination angles. Figure 1 presents the ratio of Taylor bubble velocity to gas drift velocity under various inclination angles (angles measured relative to the horizontal plane), with the plotted data covering multiple flow regimes and void fractions. For most flow patterns, the relative velocity of bubbles reaches its maximum at inclination angles between 15° and 45° , promoting upward migration and dissipation of bubbles. Moreover, as can be observed from the figure, an inclination angle of 15° also exhibits favorable performance for void fractions above 0.8. The relative velocity at 15° is more adaptable to variable flow velocities of different flow regimes [28–30]. Upward-inclined pipes can further remove liquid droplets entrained in the gas phase. The droplets carried by the gas coalesce into small liquid streams or large droplets and then flow back into the branch pipes under gravity and finally fall into the lower pipeline, thereby effectively reducing the liquid carryover rate of the gas pipeline.

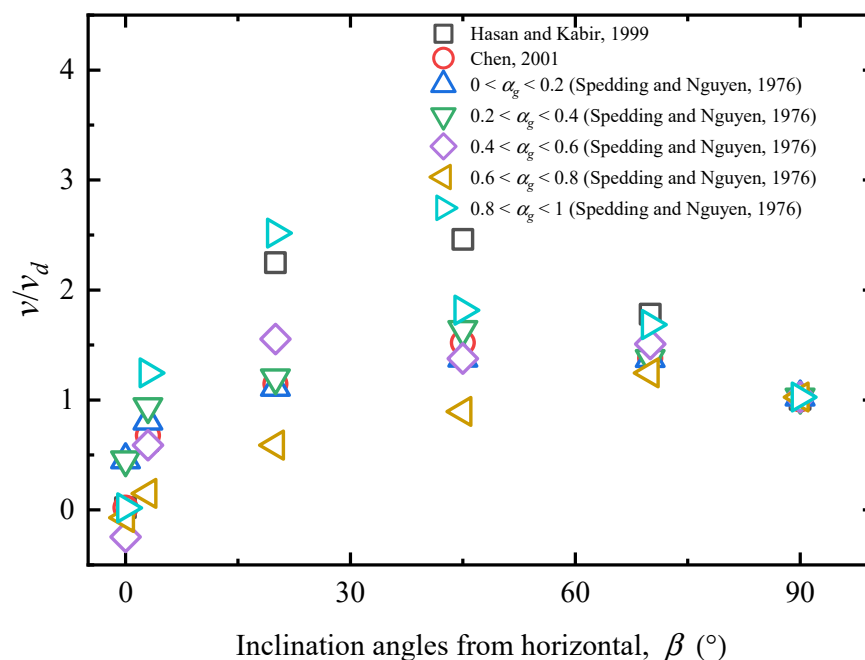


Figure 1. Taylor bubble velocities at different inclination angles [28–30]. (The vertical axis represents the ratio of Taylor bubble velocity to gas drift velocity; a larger value indicates faster upward movement of the gas phase. The horizontal axis denotes the upward inclination angle between the pipeline and the horizontal plane).

In addition, existing studies have confirmed that the number of branch pipes and the spacing between adjacent branches exert significant impacts on the separation performance of T-junctions. On the basis of the above parametric investigations, the geometric model of the T-junction was optimized as follows: A T-type branched structure with equal inner diameters for the main pipe and branch pipes was adopted, and four branch pipes were arranged at an interval of 5 pipe diameters. The upper pipe was designed to incline

upward at an angle β of 15° relative to the horizontal direction. Figure 2 shows the schematic diagram of the investigated T-junction.

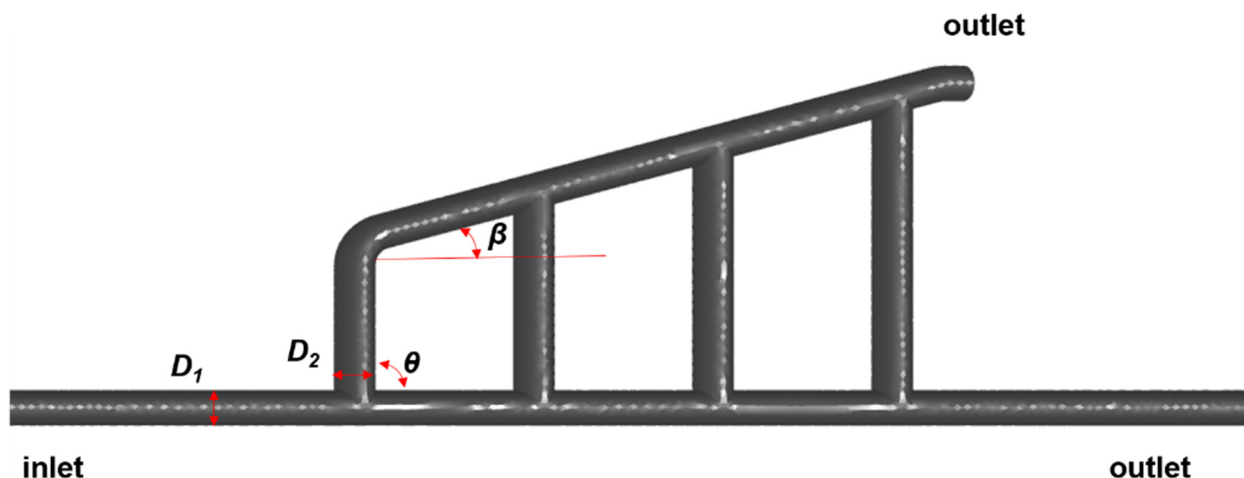


Figure 2. Schematic diagram of the general T-junction structure adopted in this study (parameters shown in the figure are determined based on the foregoing parametric analysis).

2.2. Experimental System

2.2.1. Experimental Setup

To explore the separation performance of the T-junction and its influence on downstream facilities, a T-junction assembly and a separation tank were fabricated for the experiment. The inner diameter of both the main pipe and branch pipes of the T-junction was 50 mm. The length of the horizontal main pipe from the inlet to the first branch pipe was set to $10 D$ to form a fully developed flow section. Four branch pipes were arranged along the main pipe. The height of the first branch pipe was 200 mm, and the spacing between adjacent branch pipes was $5 D$.

The separation tank was designed as a cylindrical vessel with an inner diameter of 576 mm and a total length of 1350 mm. The liquid phase inlet was arranged at $1/3$ of the total height of the head on one side of the tank and connected to the liquid outlet of the T-junction. A gas phase inlet was installed at the top of the tank along the inflow direction, which was connected to the gas outlet of the T-junction. A gas outlet and a liquid outlet with an inner diameter of 50 mm were separately arranged at the top and bottom of the rear end of the tank.

The experimental system is illustrated in Figure 3. An air compressor was used to charge air into a high-pressure gas cylinder to provide a stable gas source, and a regulating valve was adopted to adjust the gas flow rate. The liquid phase was supplied by a large-volume water storage tank, and the returned liquid was circulated back to the tank. Since the volume of the separation tank was much smaller than that of the water storage tank, the upstream water supply pressure remained stable, enabling stable and precise control of the liquid flow rate. A centrifugal pump combined with a frequency converter was utilized to control the liquid flow rate in the experimental system.

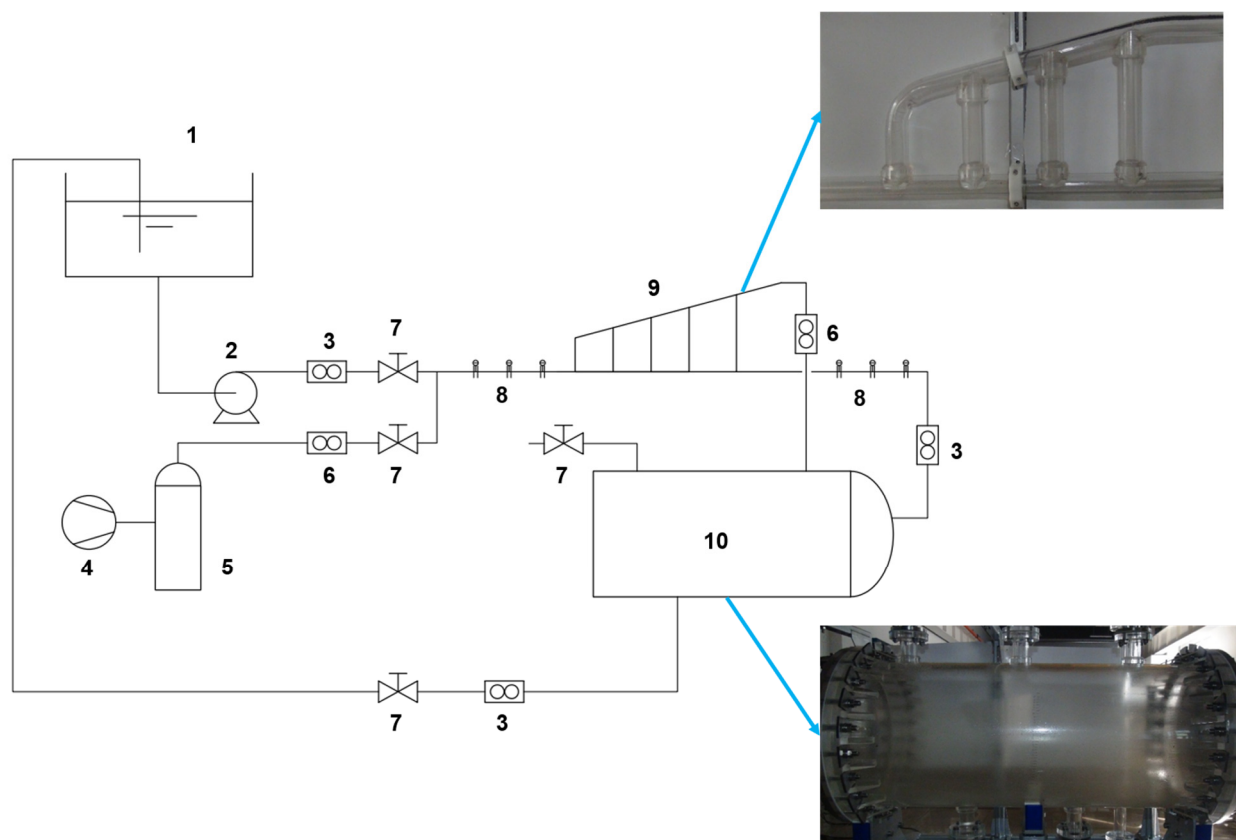


Figure 3. Schematic diagram of the experimental flow system: 1—water storage tank; 2—centrifugal pump; 3—Coriolis mass flow meter; 4—compressor; 5—gas cylinder; 6—float flow meter; 7—valve; 8—pressure sensors; 9—T-junction; 10—separation tank.

2.2.2. Monitoring System and Data Processing Method

To evaluate the gas–liquid separation performance and slug flow suppression effect, the phase flow rates at the inlet and outlet of the test system as well as the pressure distribution along the T-junction were monitored. Float flow meters were used to measure the gas flow rates at the gas inlet and outlet of the T-junction with an accuracy of $\pm 1\%$. The liquid flow rates were recorded using Coriolis mass flow meters, which feature a measurement accuracy of $\pm 0.1\%$.

Prior to formal tests, the separation device was commissioned to investigate the gas–liquid separation performance of the T-junction under various inflow patterns and gas–liquid ratios. Yang et al. [31] defined the separation efficiency as:

$$\eta = \left(\frac{Q_{g-upout}}{Q_{g-inlet}} - \frac{Q_{l-upout}}{Q_{l-inlet}} \right) \times 100\%, \quad (3)$$

where η is the separation efficiency; Q represents the flow rate of each phase; the subscript g denotes the gas phase, l denotes the liquid phase, upout represents the upper gas outlet, and inlet refers to the pipe inlet. Sampling and measurement results indicate that under low-to-medium gas–liquid mixture superficial velocities, the liquid carryover fraction at the outlet is approximately zero, whereas under high mixture superficial velocities, the liquid fraction at the outlet increases notably. The liquid separation ratio, represented by the second term $Q_{l-upout}/Q_{l-inlet}$ in Equation (3), can reflect the degree of liquid entrainment. At low-to-medium mixture velocities, the value of this second term ranges from 0 to approximately 0.000002, resulting in an impact on the separation efficiency of less than 0.0007%. At high mixture velocities, the second term ranges from 0.000096 to 0.000173, corresponding to

an impact on the separation efficiency of approximately 0.0343% to 0.0618%. Accordingly, a simplified gas-phase separation efficiency is adopted as the key indicator to quantify gas–liquid separation performance, which is defined as:

$$\eta_g = \frac{Q_{g-out}}{Q_{g-inlet}} \times 100\%, \quad (4)$$

where η_g is the gas separation efficiency.

Honeywell pressure sensors, manufactured by Honeywell Sensing and Control (China) Co., Ltd. (Nanjing, China), were mounted at equal intervals upstream and downstream of the T-junction. The spacing between adjacent pressure transducers was fixed at 0.500 m for all cases, enabling slug velocity and length to be determined via cross-correlation of pressure signals. The collected pressure signals were further processed to obtain characteristic parameters of slug flow, including slug velocity, frequency and slug length. The sampling frequency of pressure sensors f_s was set to 1000 Hz.

A second-order Butterworth low-pass filter was employed to eliminate high-frequency noise in raw pressure signals [32]. According to the dominant frequency range of slug flow concerned in this study, the cut-off frequency f_c was set to 10 Hz. In accordance with the Nyquist sampling theorem, the Nyquist frequency f_N , i.e., the maximum identifiable signal frequency, was half of the sampling frequency:

$$f_N = \frac{f_s}{2}, \quad (5)$$

The cut-off frequency was normalized to satisfy the design criteria of digital filters:

$$\Omega_c = \frac{f_c}{f_N}, \quad (6)$$

Subsequently, the bilinear transform method was adopted to convert the analog filter into a digital filter. The standard form of the discrete-time transfer function is expressed as:

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{a_0 + a_1 z^{-1} + a_2 z^{-2}}, \quad (7)$$

where z is the complex transform variable; b and a represent the feedforward coefficients and recursive coefficients of the filter, respectively.

The time-domain recursive formula was applied for signal iteration calculation.

$$y_1[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2] - a_1 y_1[n-1] - a_2 y_1[n-2], \quad (8)$$

To avoid phase shift induced by conventional one-way filtering, a forward-reverse bidirectional filtering strategy was adopted. Specifically, the original signal was first filtered in the forward direction, and then the reversed signal sequence was filtered again. Finally, the signal sequence was restored to its original order.

In addition, a liquid level gauge was installed inside the separation tank to record the liquid level variation and obtain the corresponding liquid level time-history curve.

2.2.3. Uncertainty Analysis

The major errors in the experimental study result from the measurement errors and calculation errors. The accuracy of the main instruments and equipment could be obtained from the information listed in Table 1, from which measurement errors can be derived. Measurement errors reflect the accuracy of pressure, liquid level, and flow rate. the

relationship between the uncertainty propagation of calculated parameters and measured values is shown in Equation (9):

$$\delta U = \sqrt{\sum_{i=1}^N \left(\frac{\partial U}{\partial S_i} \delta S_i \right)^2}, \quad (9)$$

where U stands for the overall uncertainty, and each S_i denotes the absolute error induced by the corresponding measurement component. Calculation results show that the overall uncertainty range of the tests is from 0.41% to 48.89%. Specifically, the uncertainty originating from flow rate measurement dominates the total uncertainty of gas–liquid separation efficiency.

Table 1. Instruments accuracy.

Parameter	Instrument	Range	Accuracy
Pressure	Pressure sensors	0–1.72 MPa	±0.5% F.S.
Liquid level	Gas–liquid interface analyzers	0–645 mm	±0.2% F.S.
Gas flow rate	Float flow meter	0–160 m ³ /h	±1% F.S.
Liquid flow rate	Coriolis mass flow meter	0–20 m ³ /h	±0.1% F.S.

2.2.4. Experimental Fluids

The gas and liquid phases used in the experiment were compressed air and an oil–water mixture with a very low oil–water ratio, respectively. The test system was maintained at an absolute pressure of 220 kPa and a temperature of 25 °C. Under such experimental conditions, the gas density was 2.45 kg/m³ and the dynamic viscosity was approximately 0.018 mPa·s. The liquid phase has a density of 990 kg/m³ and a dynamic viscosity of 6.75 mPa·s. The volume ratio of oil to water was approximately 3:100, which was used to simulate the actual high water-cut operating condition.

2.3. Numerical Simulation Methodology

With the rapid development of computational technology, numerical simulation has become a mainstream approach for investigating gas–liquid two-phase flow. Compared with physical experiments, numerical simulation can effectively reduce experimental costs and material consumption, and it also possesses excellent repeatability without the restrictions of time and space. Generally, multiphase flow models are classified into two categories: Eulerian–Lagrangian models and Eulerian–Eulerian models [33]. For gas–liquid two-phase flow simulation, the phase with a larger volume fraction is defined as the continuous phase, and the other as the discrete phase. The Eulerian–Eulerian model is suitable for the simulation of two continuous phases, which mainly include the Euler model, mixture model and Volume of Fluid (VOF) model [34]. In this study, the Eulerian model coupled with the VOF interface-tracking method is adopted for numerical simulations. This dual modeling strategy delivers distinctive advantages for gas–liquid separation inside multi-branch T-junctions, enabling simultaneous calculation of interphase slip velocities and sharp capture of gas–liquid interfaces, and it is capable of reproducing separation behaviors across all flow regimes including stratified flow, slug flow and entrainment induced by branch diversion. This model retains the core features of the Eulerian two-fluid formulation: separate continuity and momentum equations are solved for the gas and liquid phases respectively, which fully resolves the velocity difference between the two phases and accurately characterizes the inertial discrepancy and flow diversion mecha-

nism at T-branches. Meanwhile, the geometric reconstruction scheme of VOF is activated to reconstruct the gas–liquid interface by solving the volume fraction transport equation, which clearly visualizes liquid level distribution inside each branch and the overall two-phase separation process. Systematic reviews and numerical investigations in existing research have verified that the Eulerian framework combined with the VOF model can faithfully reproduce gas–liquid separation phenomena within T-junctions [35].

Turbulence models are utilized to characterize turbulent flow features. Turbulent flow consists of eddies spanning multiple scales, and flow parameters such as turbulent velocity and pressure can be solved by analyzing interactions among these eddies [36]. Widely used turbulence models for gas–liquid two-phase flow perform Reynolds averaging on the N-S equations, and they are primarily divided into eddy-viscosity models and Reynolds Stress Models (RSM) [37]. Built upon the Boussinesq hypothesis, eddy-viscosity models simplify governing equations by introducing eddy viscosity. The two-equation category covers standard k - ϵ , RNG k - ϵ , SST k - ω and other variants. The RNG k - ϵ model decomposes the N-S equations via renormalization group mathematical theory and incorporates corrections for high-shear and sharply distorted flows, making it naturally adaptable to turbulent regions featuring strong swirling flow and fluid impingement. Fang et al. [38] carried out comparative studies of multiple turbulence models under slug flow and other flow conditions for pipeline structures and validated the superior performance of the RNG k - ϵ model [39]. In this study, all numerical simulations were carried out using the commercial CFD software ANSYS Fluent 19.0, released by the ANSYS company, San Diego, CA, USA.

2.3.1. Geometric Model and Mesh Generation

To systematically investigate the gas–liquid separation characteristics and slug elimination performance of the T-junction, the computational domain was established based on the geometric dimensions of the test prototype. Figure 4a presents the basic geometry of the T-junction, which consists of a horizontal main pipe, four vertical branch pipes and an inclined upper pipe.

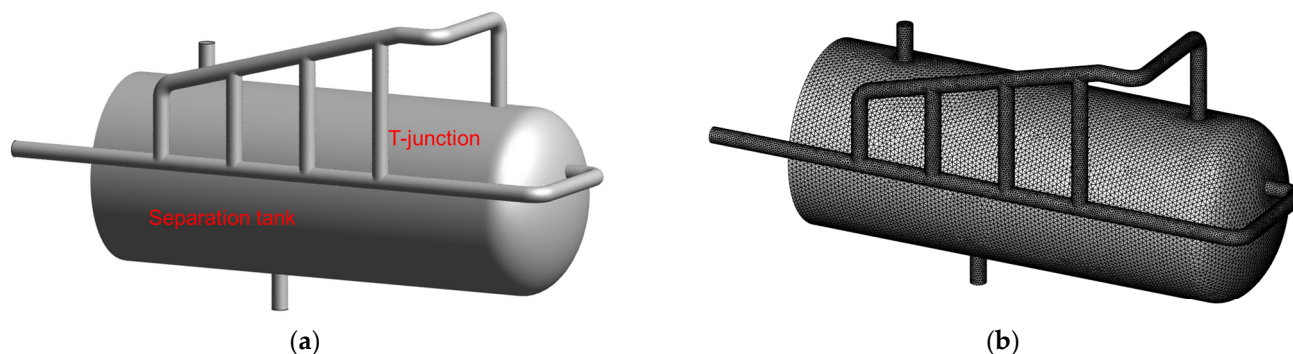


Figure 4. (a) Geometric model; (b) mesh generation.

The geometric model was meshed using the ANSYS Meshing module (version 19.0). Unstructured meshes were adopted to adapt to complex flow patterns and save computational resources, and the total number of mesh cells was approximately 1,130,000, as shown in Figure 4b. To investigate the influence of mesh resolution on the computational results, a mesh independence verification was conducted. The variations in liquid flow rate and pressure under different mesh resolutions are presented in Figure 5a and 5b, respectively. The relative deviation of characteristic parameters between adjacent mesh levels was adopted as the convergence criterion. When the relative deviation fell below 3%, the mesh was considered converged. The results demonstrate that once the mesh count

exceeded 1,130,000, both the liquid flow rate and pressure reached stable values, with the relative deviation remaining below 2.5%.

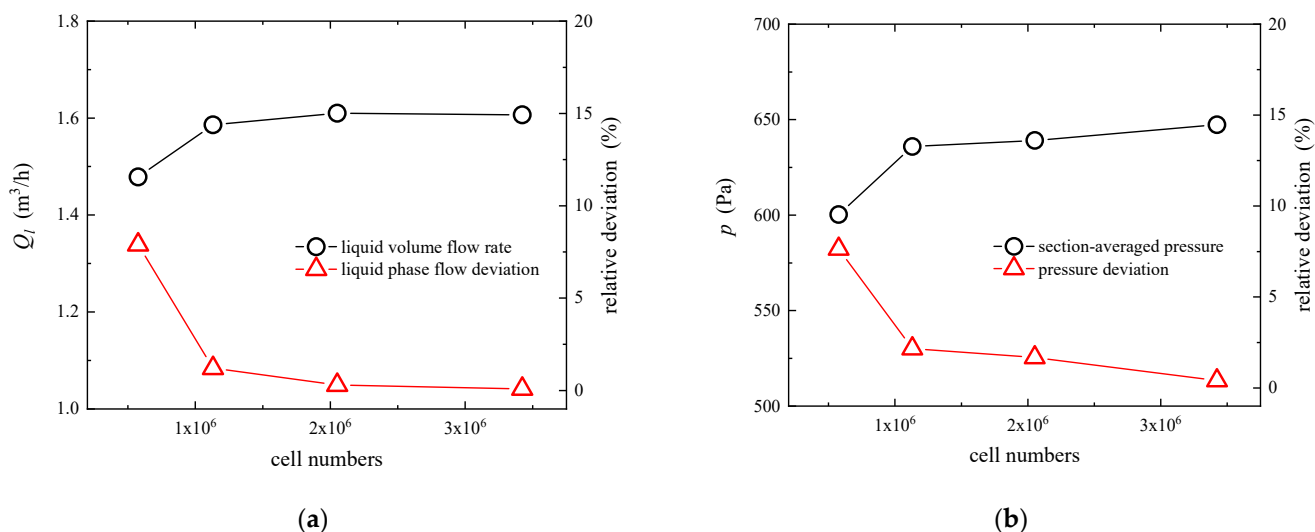


Figure 5. Mesh independence verification. (a) Flow rate analysis under different mesh schemes; (b) pressure analysis under different mesh schemes.

2.3.2. Multiphase Flow Model and Turbulence Model

The Eulerian multiphase model was employed to describe the interaction between gas and liquid phases. Both phases were treated as interpenetrating continuous media, each possessing independent velocity field, volume fraction, density and dynamic viscosity. The volume fraction of phase q is denoted as α_q , which represents the fraction of the total volume occupied by phase q . Each phase follows the mass and momentum conservation laws. The volume of phase q is expressed as:

$$V_q = \int_V \alpha_q dV, \quad (10)$$

The sum of volume fraction satisfies:

$$\sum_{q=1}^n \alpha_q = 1, \quad (11)$$

The effective density of phase q is defined as:

$$\hat{\rho}_q = \alpha_q \rho_q, \quad (12)$$

where ρ_q is the actual density of the q phase. Since no mass transfer occurs between gas and liquid phases during flow, the continuity equation for phase q is written as:

$$\frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = 0, \quad (13)$$

where $\vec{v}_q$ is the velocity vector of the q phase. The momentum conservation equation for phase q is given by:

$$\frac{\partial}{\partial t} (\alpha_q \rho_q \vec{v}_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q \vec{v}_q) = -\alpha_q \nabla p + \nabla \cdot \tau_q + \alpha_q \rho_q \vec{g} + \sum_{p=1}^n \vec{R}_{pq}, \quad (14)$$

where τ_q refers to the stress tensor of phase q , and its expressions is given as:

$$\tau_q = \alpha_q \mu_q (\nabla \vec{v}_q + \nabla \vec{v}_q^T) + \alpha_q (\lambda_q - \frac{2}{3} \mu_q) \nabla \cdot \vec{v}_q, \quad (15)$$

where λ_q stands for the volume viscosity of phase q .

The RNG k - ε model improves the standard k - ε model via statistical methods of renormalization group theory and introduces an effective viscosity to account for low Reynolds stresses, which is widely adopted in complex turbulent flow scenarios involving pipe bends and strong swirling flow [40]. Based on the Boussinesq eddy viscosity hypothesis, this model correlates Reynolds stresses with mean velocity gradients. The transport equation of turbulent kinetic energy is given by:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k \vec{v}_q)}{\partial x_q} = \frac{\partial}{\partial x_q} (\alpha_k \mu_{eff} \frac{\partial k}{\partial x_q}) + G_k + G_b - \rho \varepsilon - Y_M, \quad (16)$$

where μ_{eff} is the effective viscosity. The transport equation of turbulent dissipation rate:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon \vec{v}_q)}{\partial x_q} = \frac{\partial}{\partial x_q} (\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_q}) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon, \quad (17)$$

where G_k is the turbulent kinetic energy production term due to mean velocity gradients, and G_b corresponds to the production term from buoyancy. Y_M describes the effect of turbulent dilatation on the total dissipation rate for compressible flows. These parameters are identical to those used in the standard k - ε model. α_k and α_ε are the reciprocals of the effective turbulent Prandtl numbers for k and ε . R_ε denotes the additional correction term of the RNG model.

2.3.3. Fluid Properties and Boundary Conditions

The physical properties of gas and liquid phases (density and viscosity) in numerical simulations are set according to the measured parameters of experimental working fluids. Within the ranges of flow velocities and operating conditions adopted in the experiments, variations in gas–liquid interfacial properties can be neglected, and the gas–liquid interfacial tension is assumed to be a constant value of 72.8 mN/m for all simulation cases [41].

Three typical flow patterns, namely stratified flow, slug flow and high-gas-content flow, were investigated in this study and designated as Case A, Case B and Case C, respectively. To reproduce various inflow regimes consistent with the experiments, the velocity inlet boundary condition was adopted for the computational domain. Different gas and liquid superficial velocities were specified to establish the corresponding flow patterns, and the detailed velocity inlet parameters are listed in Table 2. A pressure outlet boundary condition was applied at all outlets.

Table 2. Velocity inlet conditions for each case.

Case	Mixture Velocity (m/s)	Gas Superficial Velocity (m/s)	Liquid Superficial Velocity (m/s)	Gas–Liquid Volume Flow Ratio
Case A	0.799	0.479	0.32	3:2
Case B	1.698	0.991	0.708	7:5
Case C	4.287	4.244	0.0423	100:1

A pressure-based solver was used for transient simulation with a time step of 0.001 s. The total simulation duration was set to more than 60 s to allow sufficient evolution of the flow field inside the T-junction and the liquid level in the separation tank.

3. Results and Discussion

The processing capacity of T-junctions in oil and gas production systems should be evaluated from a full life-cycle perspective. Accordingly, different gas–liquid two-phase flow patterns were adopted in both experiments and numerical simulations by adjusting the inlet gas–liquid ratio and flow velocity. The performance of the T-junction was characterized in terms of its gas–liquid splitting behavior, inlet and outlet flow rates, pressure variations, and its influence on the liquid level inside the downstream separation tank.

3.1. Gas–Liquid Separation Characteristics

Based on the analysis in Section 2, the gas separation efficiency of the T-junction was evaluated by monitoring the phase flow rates at its inlet and outlet. Figure 6 presents the average gas separation efficiency obtained from experiments and numerical simulations for Case A, B and C. It can be seen that Case A achieved the highest gas separation efficiency of nearly 100% in the experiment, and the numerical results showed a consistent trend.

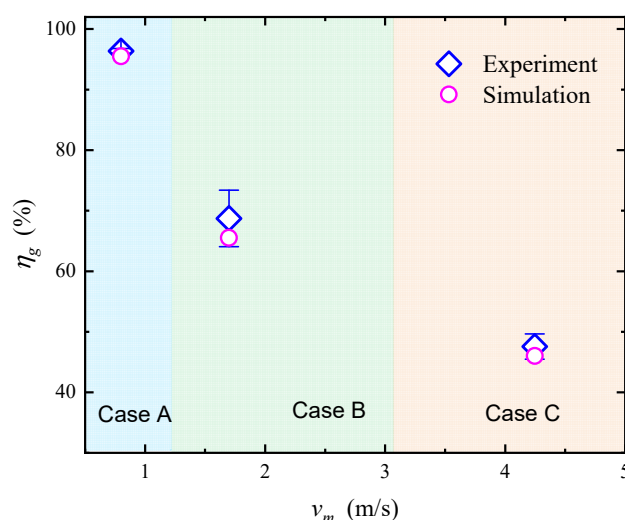


Figure 6. Average gas separation efficiency η_g of T-junction gas channel under different flow regimes.

The green region in Figure 6 corresponds to the average gas separation efficiency of Case B under slug flow conditions. Given the strong transient characteristics of slug flow, time-averaged analysis was adopted for the gas separation efficiency. The experimental data were processed based on cumulative flow rates, while the simulated results were calculated via time-weighted averaging of gas separation efficiency over several flow cycles. The gas separation efficiency of Case B decreased significantly compared with Case A, with the average value dropping below 70%. The numerical predictions followed the same variation trend and agreed well with the experimental data within the measurement error range, which verified the reliability of the numerical model. The experimental and simulated results of Case C are also illustrated in Figure 6. Under high gas fraction conditions, the gas separation efficiency of the T-junction further decreased to less than 50%. A comprehensive comparison of the errors between numerical simulations and experimental results shows that the percentage errors between simulated and measured values for Cases A, B, and C are 0.89%, 4.62%, and 3.27%, respectively, while the corresponding experimental errors for the three cases are $\pm 0.41\%$, $\pm 4.67\%$, and $\pm 2.1\%$, respectively. The deviation of the simulated value for Case A is slightly higher than the experimental error, whereas the results for the other two cases are in good agreement. Yang et al. [42] reported the same phenomenon. At low flow velocities, well-defined stratified flow formed in pipelines, leading to high separation efficiency. Increasing flow velocity broke stratified flow and

induced phase mixing, narrowing the phase flow rate gap between main and branch pipes and reducing gas separation efficiency.

To further investigate the actual gas separation behavior of the T-junction, the transient gas separation efficiency of the system was analyzed. Figure 7 shows the transient gas separation efficiency for the three cases. For Case C, the variation amplitude of gas separation efficiency was the smallest at approximately 4%, while the fluctuation occurred at a high frequency. This phenomenon was attributed to the low liquid content in this case. The separated gas phase inside the T-junction remained relatively stable, and minor fluctuations in pressure or flow rate led to slight changes in the calculated gas separation efficiency. In addition, a small number of liquid droplets adhered to the pipe wall. When large droplets or intermittent liquid streams formed, they also imposed a slight influence on the gas separation efficiency. In contrast, the gas separation efficiency of Case A varied gently and stayed above 90% throughout the operation, indicating that a large quantity of gas was diverted by the branch pipes and continuous liquid flow was maintained in the lower main pipe. Case B exhibited the most drastic fluctuation of gas separation efficiency, with the variation range exceeding 70%, which was closely related to the inherent transient characteristics of slug flow. As shown in Figure 7b, the gas separation efficiency varied periodically, matching the cycle of slug movement. When liquid slugs flowed into the T-junction, the branch pipes diverted a large amount of gas, showing similar performance to Case A. When gas pockets passed through, a certain amount of gas entered the lower pipe, resulting in a reduction in gas separation efficiency.

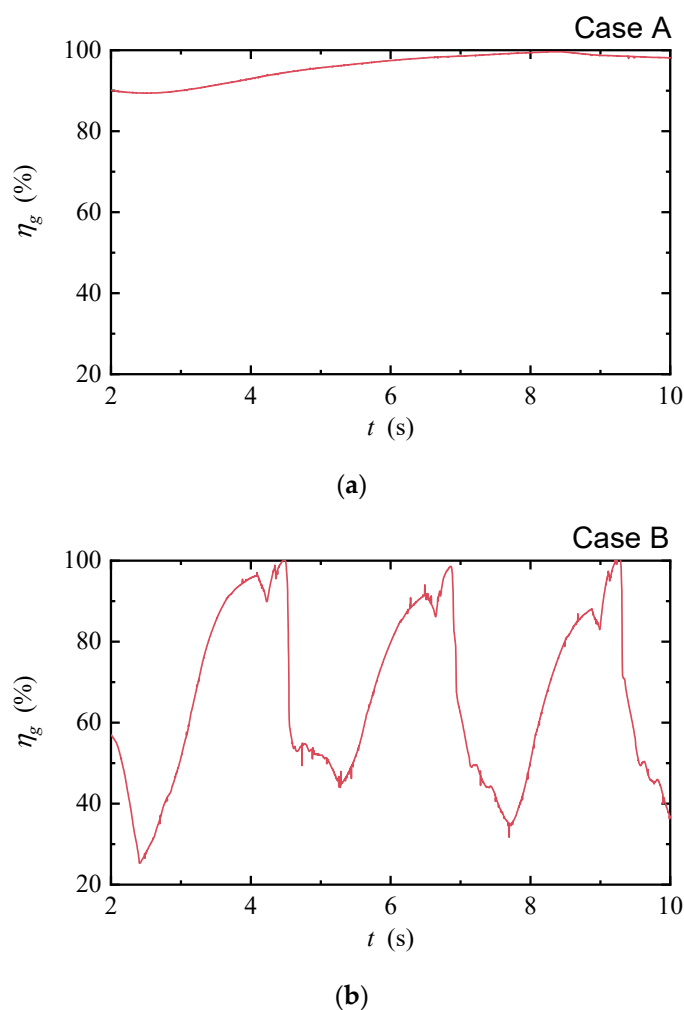


Figure 7. Cont.

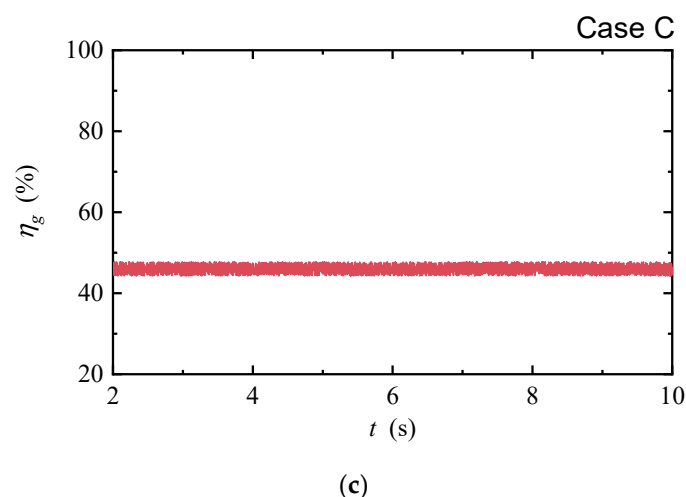


Figure 7. Evolution of transient gas separation efficiency (red solid lines) in T-junction gas channel under different flow regimes: (a) Mixture velocity = 0.799 m/s, gas–liquid ratio = 3:2; (b) mixture velocity = 1.698 m/s, gas–liquid ratio = 7:5; (c) mixture velocity = 4.287 m/s, gas–liquid ratio = 100:1.

Figure 8a presents the simulated liquid distribution contour downstream of the T-junction for Case A. Only a small fraction of gas accumulated at the top of the pipeline, while the lower pipeline contained nearly no gas, only intermittent bubbles. This indicates that most gas was diverted to the upper section via the branch pipes after passing through the T-junction. The majority of bubbles and continuous gas phase were removed from the main pipe, leaving continuous water flow in the lower pipe with occasional entrained small bubbles. Figure 8b revealed good agreement between numerical and experimental results, proving that the T-junction achieved excellent gas separation characteristics of Case A.

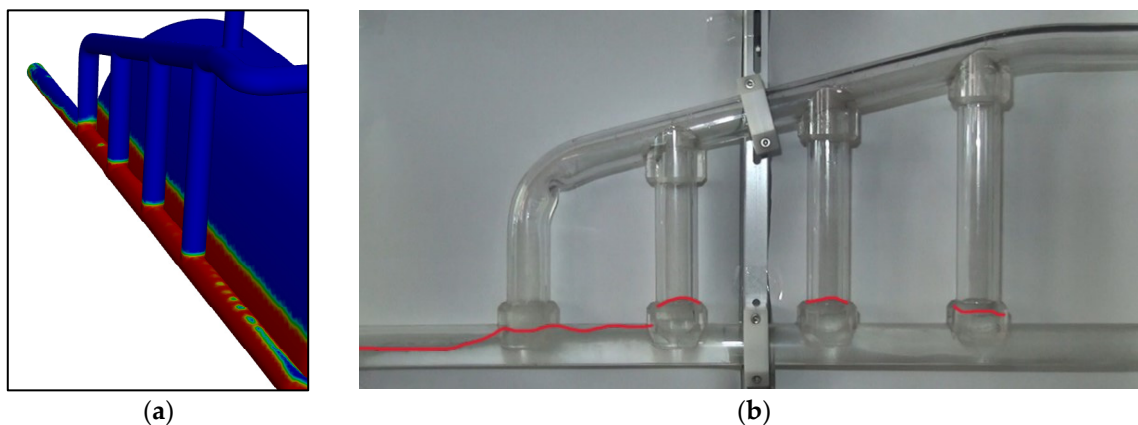


Figure 8. Liquid distribution downstream of T-junction (Case A): (a) simulation contour (red represents liquid, and blue represents gas); (b) experimental measurement (the red line represents the gas–liquid interface).

Figure 9 illustrates the evolution of liquid phase distribution for Case B. When a liquid slug first entered the front branches of the T-junction, the liquid column rose. As the flow continued, the rear branch pipes undertook flow division, which alleviated the impact and pressure of the liquid slug. The liquid column gradually fell back, and the transient intensity of the flow was weakened. The four branch pipes effectively mitigated slug flow and improved flow stability. Meanwhile, the upward inclined structure facilitated the liquid to flow back under gravity and reduced the liquid fraction in gas branches. Both experimental tests and numerical simulations confirmed that the liquid fraction in gas branches was zero for Case B.

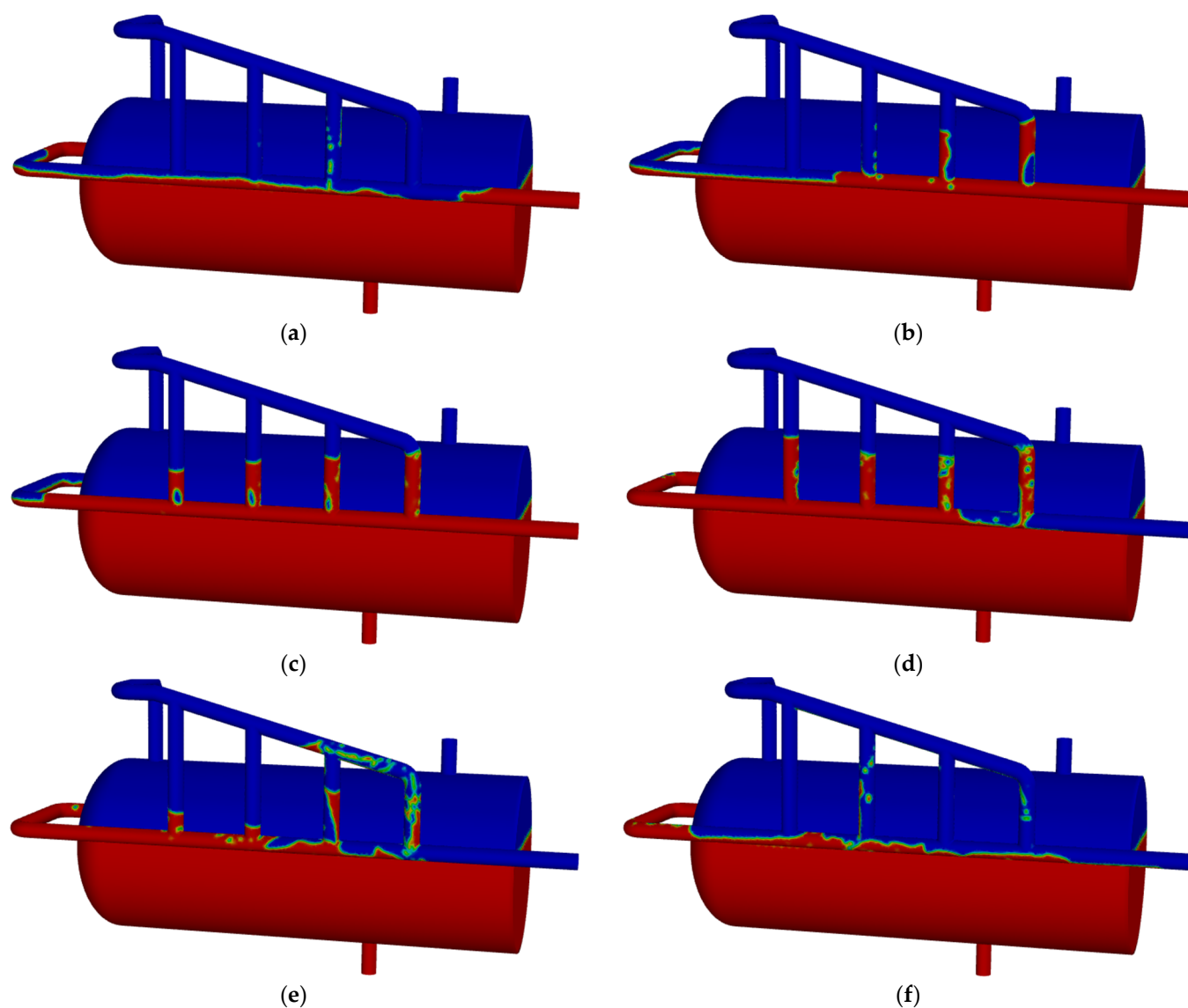


Figure 9. Liquid distribution in the T-junction and the separator (Case B), period = 2.4 s: (a) 0.4 s; (b) 0.8 s; (c) 1.2 s; (d) 1.6 s; (e) 2.0 s; (f) 2.4 s. (red represents liquid, and blue represents gas).

Figure 10 illustrates the liquid distribution inside the T-junction under slug flow. Within one slug cycle, the liquid distribution across multiple branch pipes and the lower horizontal pipeline matched the simulation results. A liquid column first flowed into the upstream branch pipe, followed by sequential liquid column rise in downstream branches, with the peak liquid height gradually declining toward the far end. A fraction of liquid surged upward from the front branch into the upward inclined pipe, while most liquid flowed back down through the second branch pipe.

Figure 11a,b display the liquid distribution from simulation and experiment of Case C, respectively. At high gas–liquid ratios, tiny liquid droplets coalesced under gravity, migrated downstream with the gas stream, and gradually accumulated into a continuous liquid layer, forming a distinct thin liquid film downstream of the T-junction.

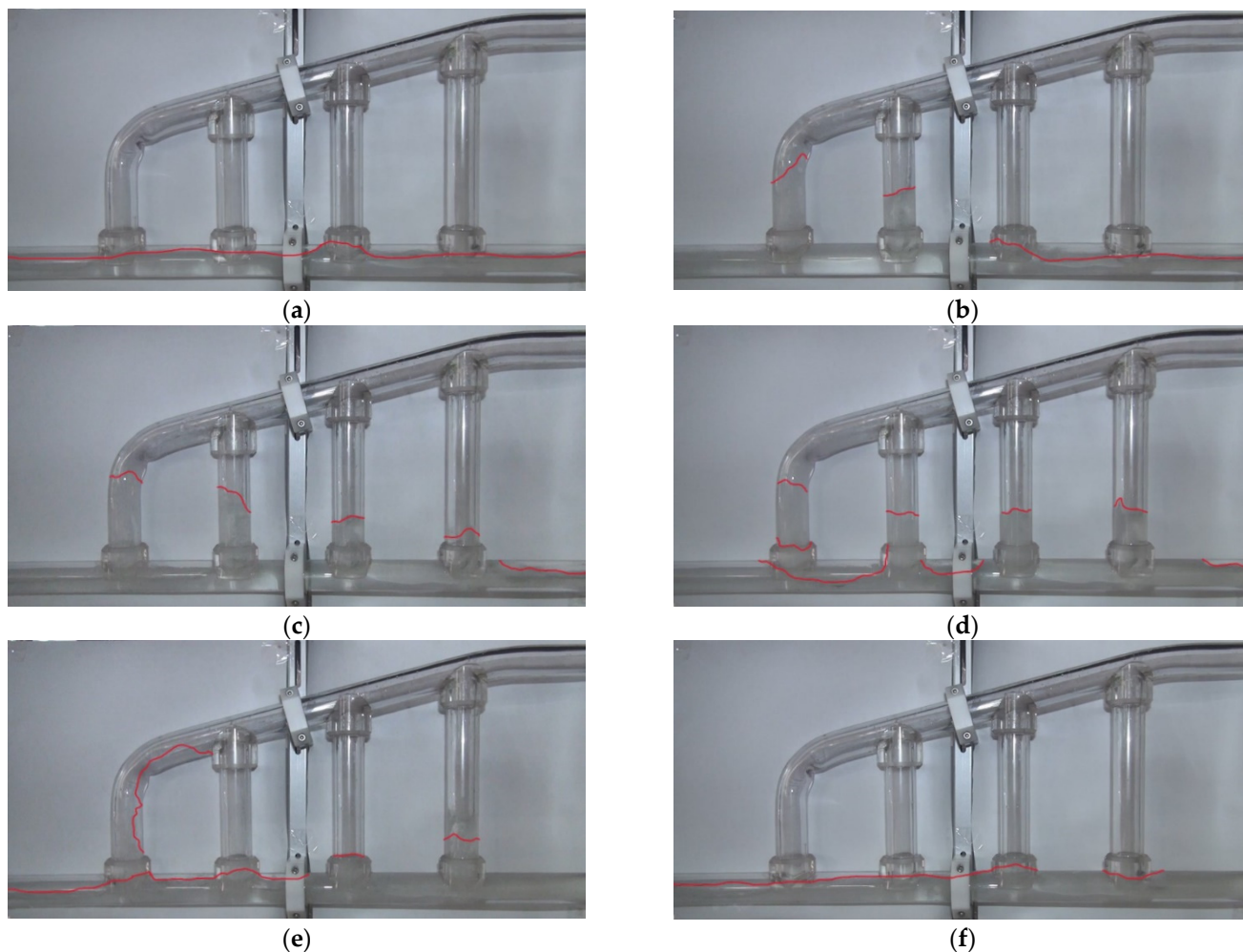


Figure 10. Liquid distribution in the T-junction of Case B in experiments: (a) 0.5 s; (b) 0.8 s; (c) 1.3 s; (d) 1.6 s; (e) 2.0 s; (f) 2.5 s. (The red line represents the gas–liquid interface).

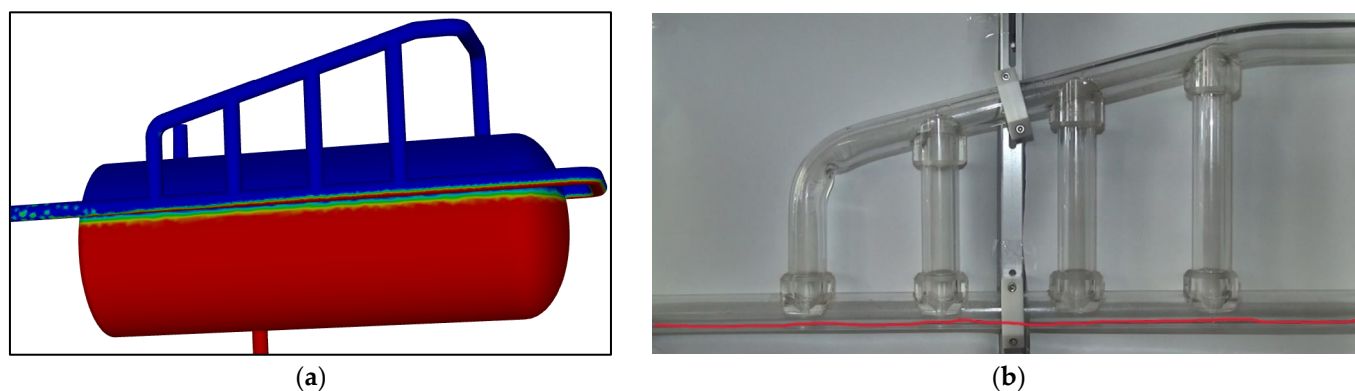


Figure 11. Liquid distribution inside T-junction (Case C): (a) simulation contour (red represents liquid, and blue represents gas); (b) experimental measurement (the red line represents the gas–liquid interface).

It should be noted that the separation performance of T-junctions is highly correlated with gas and liquid superficial velocities as well as flow patterns, and better separation efficiency can be achieved under stratified flow conditions. Reviewing the theoretical research on two-phase splitting at T-junctions, Penmatcha et al. [18] extended the applicable range of the phase splitting model based on the momentum equation with the gravitational effect of the liquid phase taken into account. Hart et al. [43] proposed a two-streamline

model. By distinguishing the streamlines along which the gas and liquid phases separately flow toward the downstream main pipe and branch pipes, they established a model based on Bernoulli's equation. Analysis indicates that the split fractions of liquid and gas entering the branch pipes are related to the ratio of gas–liquid kinetic energy and the Froude number at the inlet. Well-defined stratified flow enables the gas phase to migrate along the upper flow path into the branch pipes. At high superficial velocities, gas and liquid are fully mixed, requiring longer residence time for mass transfer driven by gravity before the two phases flow into downstream pipelines.

3.2. Liquid Level Evolution Inside Separation Tank

Slug flow poses a major threat to process equipment due to impact loads. When liquid slugs struck facilities such as inlets, elbows and valves abruptly, their velocity dropped to zero within an extremely short time. The resultant momentum change exerts a severe impact on equipment and might induce intense structural vibration. Furthermore, the instantaneous liquid inflow upon slug arrival could exceed the normal liquid discharge capacity of downstream units, causing a sharp rise in liquid level. This would trigger adverse effects including equipment oscillation and even potential damage.

Figure 12 illustrates the liquid level variations at the middle and rear sections of the separation tank under Case A, B and C. The liquid level is expressed in a dimensionless form defined as the ratio of gas–liquid interface height to the tank diameter. Figure 12a shows the level fluctuation under stratified flow, with a typical amplitude of several millimeters and a moderate rate of change, without abrupt fluctuations. Figure 12b presents the level variation under slug flow, which is violent with a fluctuation range of several centimeters. Figure 12c corresponds to the condition with high gas fraction and high flow velocity. The incoming liquid volume was extremely small, exerting little influence on the liquid level, which declined steadily.

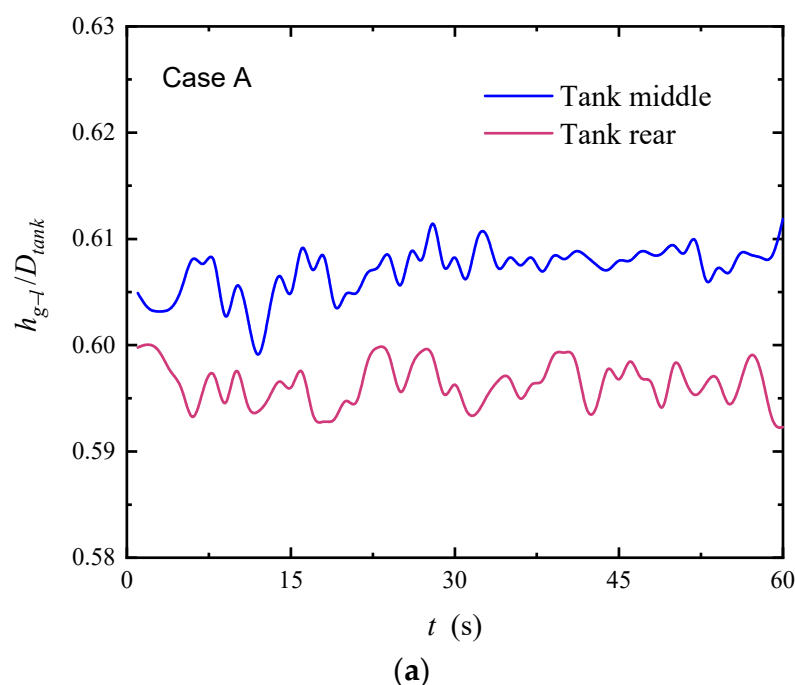


Figure 12. Cont.

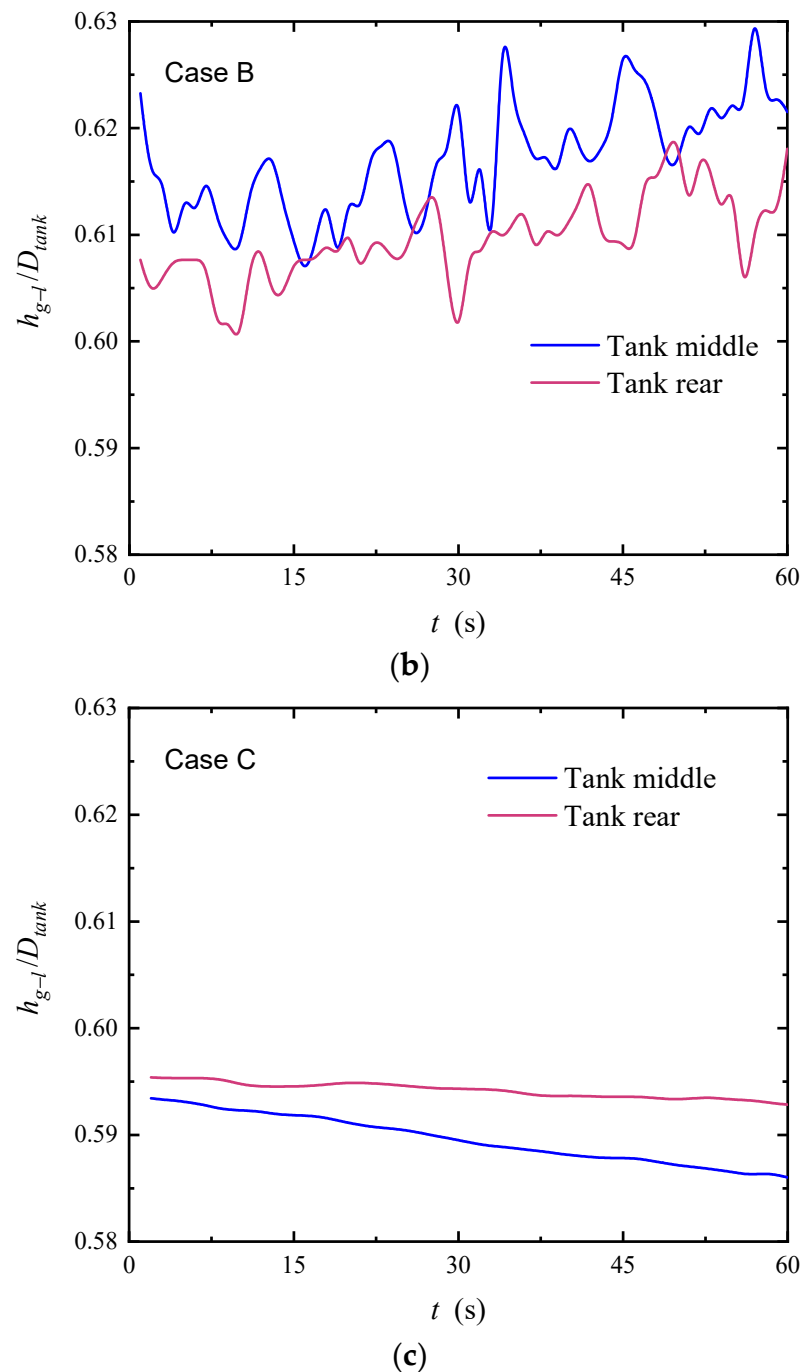


Figure 12. Liquid level variation in separation tank: (a) Case A; (b) Case B; (c) Case C.

Figure 13a,b show photos of the instantaneous gas–liquid interface inside the test tank for Case A and Case B, respectively. The plotted red and blue lines mark the gas–liquid interface boundaries on the two radial sides of the tank. For Case A, the liquid surface was generally flat without obvious fluctuations, and the liquid levels on both sides were nearly identical. In contrast, a noticeable height difference appeared on the liquid surface for Case B. Affected by the drastically fluctuating inlet flow velocity, the liquid surface exhibited distinct transient characteristics. Housner [44] proposed an equivalent lumped mechanical branch model for liquid–structure coupling in storage tanks, which divides the liquid mass into an impulsive mass and a sloshing mass to describe the impulsive and convective loads acting on the tank, respectively. This model correlates liquid level

fluctuations with structural forces, demonstrating that larger liquid level oscillation ranges introduce more adverse impacts on the tank structure.

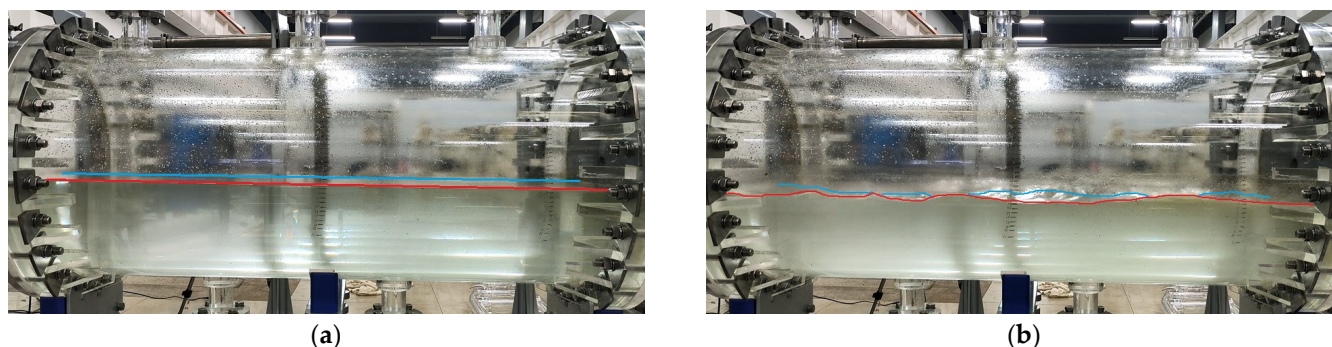


Figure 13. Instantaneous gas–liquid interface inside the tank in experiment: (a) Case A; (b) Case B. The red and blue lines mark the gas–liquid interface boundaries on the two radial sides of the tank.

Figure 14 presents the difference between the maximum and minimum liquid levels for each case obtained from experiments and simulations. It further indicates that slug flow produced the largest and most violent liquid level variation within the investigated range, with obvious discrepancies among different cases. For Case A, the incoming liquid flow rate was relatively high, leading to liquid level fluctuations lower than those in Case B but higher than those in Case C.

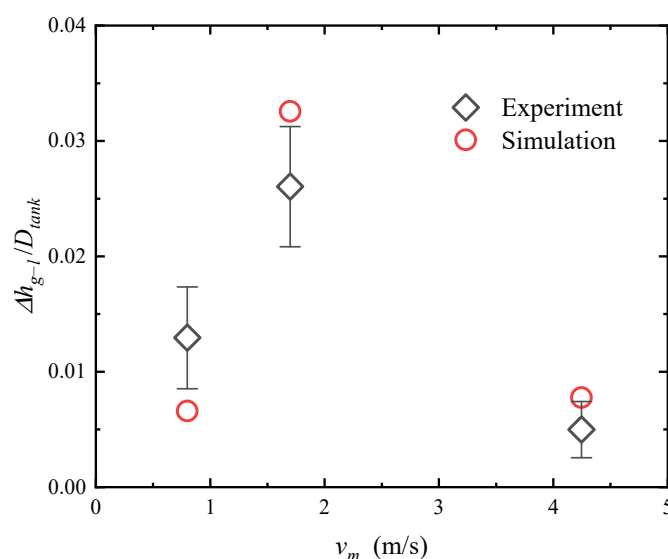


Figure 14. Liquid level variation under different flow patterns.

According to Moffat’s uncertainty propagation analysis [45], the combined standard uncertainty of the dimensionless liquid level variation is expressed as:

$$U(\zeta_{\text{exp}}) = \frac{U(\Delta h_{g-l})}{D_{\text{tank}}}, \quad (18)$$

where λ denotes the variation in the relative liquid level. The uncertainty of the liquid level variation is:

$$U(\Delta h_{g-l}) = \sqrt{U_A^2(\Delta h_{g-l}) + U_B^2(\Delta h_{g-l})}, \quad (19)$$

where $U_A(\Delta h_{g-l})$ and $U_B(\Delta h_{g-l})$ are the Type A and Type B standard uncertainties of the liquid level change, respectively.

The relative deviation between the simulated and measured values is defined as:

$$\gamma = \frac{|\zeta_{sim} - \bar{\zeta}_{exp}|}{\bar{\zeta}_{exp}} \times 100\%, \quad (20)$$

Based on the average experimental values, the relative errors between the numerical predictions and the test averages for Cases A, B, and C are 48.96%, 25.04%, and 55.71%, respectively. This relatively large discrepancy for Case C is mainly attributed to the smaller experimental uncertainty in that case. For the same absolute difference between simulation and experiment, the relative deviation becomes larger. When the measurement uncertainties are taken into account, the confidence intervals of the experimental results are revised, and the relative errors between simulation and measurement are reduced to 22.6%, 4.19%, and 4.58%, respectively.

The impact of the T-junction on separator liquid level oscillations reflects its practical engineering significance: it realizes upstream gas–liquid pre-separation to alleviate intense downstream flow disturbances and lower liquid sloshing loads. Tubular pre-separation also speeds up separation and delivers superior separation fineness, allowing smaller equipment sizes that fit compact industrial spaces. Further systematic research is necessary when applying such tubular components to complex flows and flow rates outside the test conditions examined here.

3.3. Performance of Slug Mitigation

3.3.1. Evolution of Slug Velocity

The main factors affecting liquid slug velocity include gravitational acceleration, pipe diameter, gas–liquid flow rates and liquid properties. The liquid slug velocity fluctuates drastically over time. Statistical analysis is therefore required to obtain the steady-state liquid slug velocity v_s . After the adjacent pressure signals acquired in the experiment were processed into differential pressure signals, the time lag τ between the upstream and downstream positions could be determined, and the velocity of the liquid slug front could be calculated, which was regarded as the steady slug velocity.

Figure 15 presents the filtered time-history curves of differential pressure measured by adjacent sensors upstream and downstream of the T-junction under Case B. The black curves represent the former differential pressure signals and the red curves represent the latter ones, and cross-correlation analysis was performed on the two groups of signals. The data from 1.5 s to 3.5 s in Figure 15a were enlarged in Figure 16. It is observed that the two differential pressure signals follow identical variation trends with a certain time lag. Let a be the sudden-rise time of Differential Pressure Signal 1 and b be that of Differential Pressure Signal 2; the time lag τ is defined as the time interval from a to b [46–48].

The liquid slug velocity is calculated using the following equation:

$$v_s = \frac{L_p}{\tau}, \quad (21)$$

where L_p denotes the spacing between adjacent pressure sensors.

The value of L_p in Equation (21) is specified in Section 2.2.2, which equals 0.500 m for all test cases. A total of nine complete sets of differential pressure data corresponding to liquid slug movement were extracted from Figure 15a,c,e. The calculated liquid slug velocities ranged from 1.08 m/s to 2.78 m/s, with an average value of 1.796 m/s. The relative deviation from the mixture velocity was approximately 5.8%, which proved that the mixture velocity could be used as a reasonable approximation for liquid slug velocity. In addition, liquid slug velocity was generally higher than mixture velocity, which was

consistent with the findings in this study. Table 3 lists the slug time lag and corresponding velocity upstream of the T-junction as shown in Figure 15. The time taken for slugs to pass through two adjacent differential pressure monitoring sections ranged from 0.18 s to 0.462 s, showing obvious transient characteristics related to the slug structure passing through the measuring points. The reduction effect of the T-junction on slug velocity is primarily manifested in the dispersion of slug kinetic energy through flow diversion. The branching configuration distributes the momentum of the two-phase flow among multiple branch pipes, thereby reducing the propagation velocity of liquid slugs in the main pipe. In addition, local flow resistance exists at the T-junction, generating additional pressure drop as the liquid slug passes through. This pressure drop further dissipates the kinetic energy of the slug. The observed variations in differential pressure indicate that the liquid slug undergoes a significant deceleration process after passing through the T-junction.

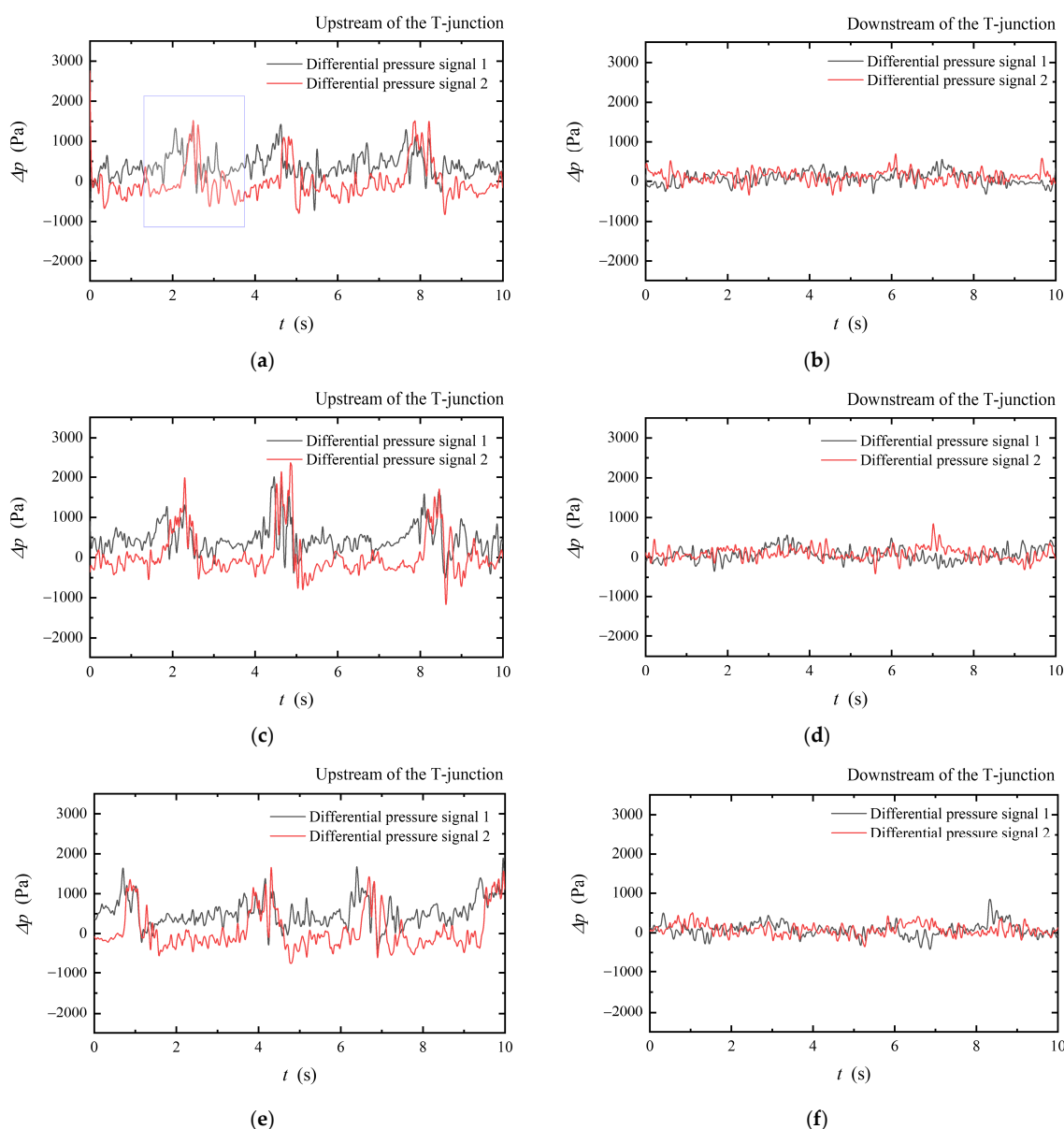


Figure 15. Time-history curves of differential pressure upstream and downstream of T-junction: (a) test period 1, upstream of T-junction (the area within the pink frame is enlarged to serve as a typical example); (b) test period 1, downstream of T-junction; (c) test period 2, upstream of T-junction; (d) test period 2, downstream of T-junction; (e) test period 3, upstream of T-junction; (f) test period 3, downstream of T-junction.

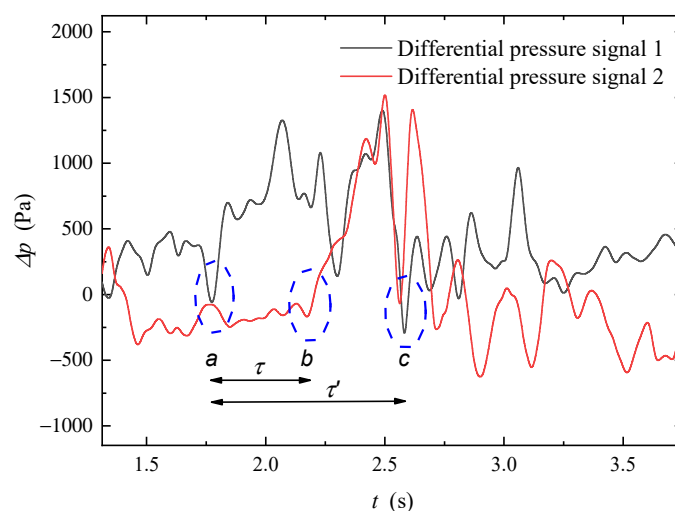


Figure 16. Partial enlarged view of Figure 15a (1.5 s–3.5 s), a, b, and c correspond to the typical characteristic instants of differential pressure signals 1 and 2, respectively.

Table 3. Time lag and liquid slug velocity of multiple slugs.

Slug No.	τ (s)	v_s (m/s)
1	0.394	1.269
2	0.404	1.237
3	0.180	2.779
4	0.236	2.119
5	0.238	2.104
6	0.462	1.082
7	0.250	2.002
8	0.261	1.912
9	0.302	1.658

Figure 15b,d,f show the differential pressure signals downstream of the T-junction. The downstream differential pressure varied gently without obvious peak fluctuations compared with the upstream data. Its magnitude was generally within 1000 Pa, mostly at several hundred Pa. This indicated that the T-junction effectively weakened the transient effect of slug flow and yielded highly stable flow in the downstream pipeline.

Slug velocity variation can reflect the slug attenuation performance. Lower slug velocity reduces the rate of liquid level fluctuation inside the tank, which helps mitigate the dynamic loads exerted on downstream equipment. The outlet flow velocity could be calculated from the outlet flow rate and void fraction of the T-junction. In terms of energy conservation, the total mechanical energy upstream of the T-junction equals the sum of mechanical energy in each downstream branch plus the energy loss along the flow path (including friction loss, turbulent dissipation, and shape drag loss induced by branch geometry). Based on Bernoulli's equation:

$$v_{inlet} D_{inlet}^2 = v_{upout} D_{upout}^2 + v_{lowout} D_{lowout}^2, \quad (22)$$

$$\rho_{inlet} g h_{inlet} + p_{inlet} + \frac{\rho_{inlet} v_{inlet}^2}{2} = \rho_{lowout} g h_{lowout} + p_{lowout} + \frac{\rho_{lowout} v_{lowout}^2}{2} + \frac{\Delta E_{inlet-lowout}}{dV}, \quad (23)$$

$$\rho_{inlet} g h_{inlet} + p_{inlet} + \frac{\rho_{inlet} v_{inlet}^2}{2} = \rho_{upout} g h_{upout} + p_{upout} + \frac{\rho_{upout} v_{upout}^2}{2} + \frac{\Delta E_{inlet-upout}}{dV}, \quad (24)$$

where h denotes elevation, the subscript inlet stands for the inlet, upout for the upper outlet, and lowout for the lower outlet. The final term in the formula represents the path energy loss per unit volume. Reduced downstream liquid flow rate and void fraction led to a decline in mixture velocity, and the separated gas carried away part of the incoming flow energy at the inlet. Nearly pure gas could be separated downstream via a shorter flow path, eliminating alternating gas–liquid flow impacts on the vessel and drastically weakening the adverse effects of slugs.

3.3.2. Evolution of Slug Length

Point c in Figure 16 denotes the time when the sharp rise in the upstream differential pressure signal fades and the signal becomes stable. The time interval between a and c is defined as the slug transit time τ' , and the liquid slug length L_s is calculated as follows:

$$L_s = v_s \tau' - L_p, \quad (25)$$

Table 4 lists the slug transit time and corresponding slug length upstream of the T-junction presented in Figure 15. The minimum and maximum slug lengths were 0.46 m and 2.2 m, respectively. Slug flow impacts piping and downstream facilities via impulse loads on pipe and vessel walls induced by alternating long liquid slugs and gas bubbles. Variations in slug length and velocity alter the transit time of slugs or bubbles past a fixed measuring point. After passing through the T-junction, liquid velocity drops, enabling effective slug attenuation.

Table 4. Transit time and slug length of multiple slugs.

Slug No.	τ' (s)	L_s (m)
1	0.825	0.547
2	0.777	0.461
3	0.970	2.195
4	0.971	1.557
5	0.840	1.267
6	1.230	0.834
7	0.698	0.897
8	1.100	1.609
9	0.926	1.036

3.3.3. Evolution of Slug Frequency

The slug period can be determined by extracting the time intervals between the rising or falling points of adjacent differential pressure signals in Figure 15, and the slug frequency was obtained by taking the reciprocal of the period. For Case B in the experiment, the inlet slug frequency ranged from 0.272 Hz to 0.417 Hz, with an average value of 0.349 Hz.

Figure 17 shows the simulated differential pressure curves for Case B. The inlet slug period remained relatively stable at approximately 2.4 s, which was mainly governed by the inlet boundary conditions. Figure 17b presents the differential pressure signals downstream of the T-junction. The sharp pressure rises are obviously weakened and their duration is shortened, demonstrating that the T-junction in the numerical simulation can effectively suppress slug flow. When liquid slugs reach the multi-branch zone of the T-junction, the continuous liquid columns are split and cut by branch pipes, which greatly reduces the momentum impact carried by individual liquid slugs. Meanwhile, the upward inclined gas collecting branches provide an independent upward migration path for the gas phase, allowing a large amount of gas to separate and discharge in advance. This markedly weakens the alternating impact of gas and liquid inside the downstream main

pipe. The sharp instantaneous pressure peaks induced by intact upstream slugs essentially stem from the instantaneous energy concentration caused by the momentum difference between gas and liquid phases. Subject to the dual effects of multi-branch flow splitting and pre-stratification of gas and liquid, the fluid energy is dissipated and dispersed. As a result, the peak differential pressure and the duration of pressure fluctuations downstream are both reduced, and the violent periodic pressure oscillations triggered by slugs are effectively alleviated.

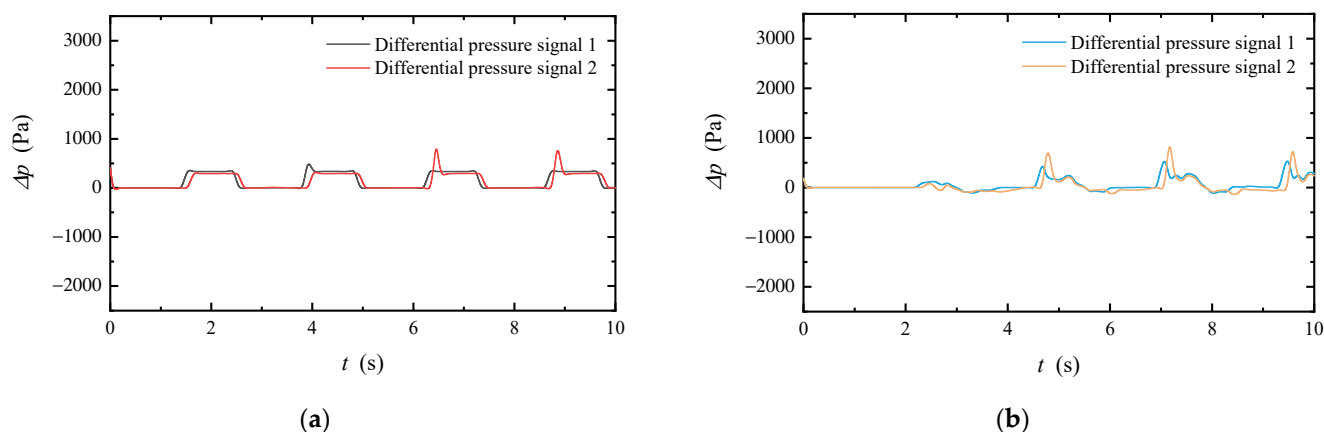


Figure 17. Simulated differential pressure signals of T-junction: (a) upstream of the T-junction; (b) downstream of the T-junction.

However, key slug characteristic parameters including slug frequency and slug length relevant to the T-junction proposed in this study remain to be further discussed. The mitigation performance of such pip-type structures under faster and longer liquid slugs still lacks sufficient investigation. Future research will focus on identifying the critical governing parameters affecting the gas–liquid two-phase separation performance of T-junctions, as well as verifying the applicability of these parameters after geometric scale-up.

4. Conclusions

This study systematically investigated the gas–liquid separation and slug suppression performance of an optimized T-junction configuration under various inlet flow patterns and superficial velocities. The optimal structure was determined through parametric sensitivity analysis. A combined experimental and numerical approach was adopted. Flow rates and pressures were measured at the pipeline inlet and outlet, and liquid levels were monitored in the downstream separator. These measurements enabled a comprehensive evaluation of the practical effectiveness of the proposed structure.

Through parametric sensitivity analysis, the optimal configuration was identified as a T-junction with four vertical branch pipes, in which the upward main pipe was inclined at 15° relative to the horizontal plane. At an operating pressure of 220 kPa, under low mixture velocities (≤ 0.799 m/s), the proposed structure achieved flow stratification across all tested conditions. This enabled highly efficient gas–liquid pre-separation, with the gas separation efficiency consistently maintained above 90%. Under slug flow conditions, the time-averaged gas separation efficiency decreased to approximately 68%, while the instantaneous efficiency exhibited significant time-varying characteristics and fluctuated between 25% and 100%. At high mixture velocities and high gas volume fractions ($>99\%$), the separation efficiency experienced a further decline. Nevertheless, it remained above 40% and exhibited relatively stable behavior.

The T-junction effectively mitigated liquid level fluctuations in the downstream separation equipment. Comparative tests across various operating conditions revealed that

slug flow exerted a more pronounced impact on downstream liquid level stability than other flow patterns. Specifically, slug flow induced severe liquid level oscillations within the downstream separator. These oscillations generated additional pressure loads and triggered internal fluid sloshing. However, the proposed T-junction attenuated these adverse effects by reducing the slug velocity and shortening the slug length downstream of the junction. It also moderated the intense transient pressure fluctuations and momentum variations that are characteristic of slug flow. This protective function ensures reliable safeguarding of downstream facilities while accelerating the gas–liquid separation process and maintaining stable operation of the entire system.

Numerical simulations of the T-junction demonstrated good agreement with experimental data. The Eulerian two-fluid model coupled with the RNG $k-\varepsilon$ turbulence model proved capable of accurately capturing the gas–liquid flow behavior within the T-junction. The differential pressure signals enabled effective characterization of slug evolution dynamics. Using the monitored slug signals at the inlet, the slug parameters were successfully reconstructed through inverse analysis. The simulated slug treatment results exhibited consistent suppression performance. These findings further corroborate the pre-separation advantages of the proposed T-junction configuration.

Author Contributions: Conceptualization, Y.C. and S.L.; Methodology, H.Y. and J.X.; Software, M.Y.; Validation, M.Z. and H.Y.; Formal Analysis, M.Y.; Investigation, Y.J. and Y.Y.; Resources, Y.J. and Y.Y.; Data Curation, M.Y. and S.L.; Writing—Original Draft, M.Y.; Writing—Review & Editing, J.X.; Visualization, Y.C.; Supervision, M.Z. and J.X.; Project Administration, M.Z.; Funding Acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CFD	Computational Fluid Dynamics
VOF	Volume of Fluid
RSM	Reynolds Stress Models

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