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Research on Structure Optimization of T-tube oil-water Separator

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Abstract

The traditional produced liquid is separated from oil and water at the combined station, but the process has large energy consumption, high operating costs, and some of the combined stations are small in treatment scale, which is difficult to adapt to the increasing water content treatment needs. The tubular separator is used to separate the high water content free water in the produced fluid of the well site to achieve "on-site separation and on-site reinjection", which is convenient and efficient. In this paper, the flow field characteristics and separation process of T-shaped pipe are studied by numerical simulation, and the number of branch pipes, horizontal pipe diameter and branch pipe length of T-shaped pipe are optimized on this basis, and the influence of the above structural parameters on the oil-water separation effect is analyzed. The simulation in this paper is carried out under the conditions of inlet mixing flow rate of 0.1m·s-1, oil content of 5%, and split ratio of 0.5, and the main conclusions are as follows: (1) The number of branch pipes has little effect on the velocity distribution law of the oil-water two phases, and both show that in the main pipe, the speed of both phases gradually decreases with the flow direction; in the branch pipe, the speed is the highest; the water phase has a slower velocity in the top area of the main pipe (the aggregation area of the oil phase), and the oil phase has a significantly higher flow rate in this area than the water phase. In manifold pipes, the above velocity distribution trend is more pronounced. (2) The increase of horizontal pipe diameter will lead to a slower speed of the liquid in the pipe, and the slower flow speed will lead to a longer residence time of the liquid in the pipeline, so the separation effect of the oil-water mixture will decrease. The increase of the number of branch pipes and the decrease of horizontal pipe diameter can significantly improve the separation efficiency, while the increase of the length of branch pipes does not significantly improve the separation efficiency. The results of this paper are helpful to optimize the structure of T-type tubular separator in the oil-water separation process and improve the separation efficiency of the equipment.

Keywords

T-tube; Oil-water Separation; Numerical Simulation; Oil-water two-phase Flow.

1. Introduction

With the continuous advancement of petroleum exploitation, most oilfields in China have entered the middle and late stages of development, and the water cut of produced fluid in some oilfields can be as high as over 90%. Traditionally, oil-water separation of produced fluid is carried out in centralized treatment stations, but this process has high energy consumption and operation costs. Moreover, the small treatment capacity of some centralized stations makes it difficult to meet the increasing demand for handling high water-cut fluid. In response to this situation, the adoption of tubular separators to pre-separate free water from high water-cut produced fluid at well sites, realizing the new process of "on-site water separation and on-site reinjection", has become a high-efficiency and low-cost new pre-water separation process that has attracted widespread attention. For China, petroleum is an indispensable material closely related to national economic security. The amount of petroleum reserves is one of the key

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factors for sustainable development. Meanwhile, petroleum is also the backbone of creating national and social wealth, as well as one of the most important materials related to global political status, economic stability and military strength. The separation of oil-water-gas mixtures, including oily wastewater, oil spills and oil-gas content, has attracted global interest. Various technologies, such as gravity separation, membrane separation, coagulation and oil absorption processes, have been applied for the further treatment of these mixtures. However, these methods can no longer meet the application requirements in terms of treatment capacity and separation efficiency.

T-shaped separators, which mainly adopt gravity and expansion methods, can serve as a solution. T-shaped separators exhibit excellent performance due to the short fluid residence time. In fact, whether in onshore or offshore oilfields, oil and gas resources are generally transported through complex pipeline network systems [1]. A large number of T-shaped separators are installed in these complex transportation networks. When single-phase flow such as crude oil or natural gas occurs in the pipeline, the flow distribution becomes uneven after passing through these T-shaped separators under the conditions of inflow and operation [2]. When multiphase media such as crude oil, water, natural gas and condensate oil, or oil, gas and water coexist in the pipeline, the flow conditions become more complex and the phase distribution becomes uneven [3-5]. If the degree of such phase distribution unevenness can be enhanced, T-shaped separator pipes can be used as oil-water-gas pre-separators in the oil and gas industry [6].

Previous studies mostly investigated phase separation in T-junction separator pipes through experimental tests, mainly focusing on gas-liquid separation and oil-water separation. In addition, almost all existing models are either completely empirical or based on flow analysis, still relying on empirical correlations, which makes the predictability of phase separation largely dependent on specific experiments. Today, the prediction of phase distribution unevenness at pipeline junctions remains a challenging problem [7]. T-shaped pipes are a new type of three-phase flow separator developed in recent years. Simple T-shaped pipes have been applied for the preliminary separation of gas-liquid two-phase flow in chemical processes. However, their large-scale industrial application is limited due to low separation efficiency. Nevertheless, some scholars have pointed out that increasing the number of T-junction separators can improve the phase separation efficiency. Combining several T-shaped pipes to form a composite T-shaped pipe can enhance the separation efficiency of three-phase flow, and even achieve complete separation of three-phase flow [8]. In summary, this paper adopts the numerical simulation method to study the flow field characteristics and separation process inside T-shaped pipes. On this basis, the number of branch pipes, horizontal pipe diameter and branch pipe length of T-shaped pipes are optimized, and the influence law of the changes in the above structural parameters on the oil-water separation effect is analyzed.

2. Theoretical Model

2.1. Turbulence Model

RNG *k-ε* model (Renormalisation group k-ε model): Based on the modified standard *k-ε* model, this model constrains the constants in the *k-ε* model by applying physical concepts and precise turbulence theory, which improves the prediction accuracy. It is suitable for various engineering problems involving strong pressure gradients and swirling flows. The equations are as follows:

$$\frac{\partial(\rho\kappa)}{\partial t}+\frac{\partial(\rho\kappa u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\alpha_{\mathrm{k}}\mu\frac{\partial\kappa}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_K$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_J}\left[\alpha_\varepsilon\mu\frac{\partial\varepsilon}{\partial x_j}\right]+G_{1\varepsilon}\frac{\varepsilon}{\mathrm{k}}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon$$

In this formula, G_k denotes the turbulent kinetic energy generated by the average velocity gradient, while G_b represents the turbulent kinetic energy produced by buoyancy.

Y_m denotes the contribution of fluctuating expansion to the total dissipation rate in compressible turbulence;$C_{1\varepsilon}$, $C_{2\varepsilon}$ *and* $C_{3\varepsilon}$ are constants.

S_k *and* S_ε are user-defined source terms; κ denotes turbulent kinetic energy, while ε represents turbulent dissipation rate.

2.2. Physical Model

Development Prior to establishing the physical model, a two-dimensional T-tube model was developed based on practical considerations, accounting for varying local losses in T-tubes across different diameters and pressure variations in pipelines. The T-tube separator consists of three components: the main pipe, branch pipes, and collector pipe. The structural parameters of the T-tube oil-water pre-separation device are presented in Table 1, with its configuration illustrated in Figure 1. The separation equipment comprises three distinct sections: the rectangular tangential main pipe, branch pipes, and collector pipe.

Table 1. Structural Parameters of T-type Tubular Oil-water Separator

Directorial diameter	confluence diameter	Length of the main entrance section	branchial height	branchial diameter
25mm	25mm	500mm	250mm	9mm

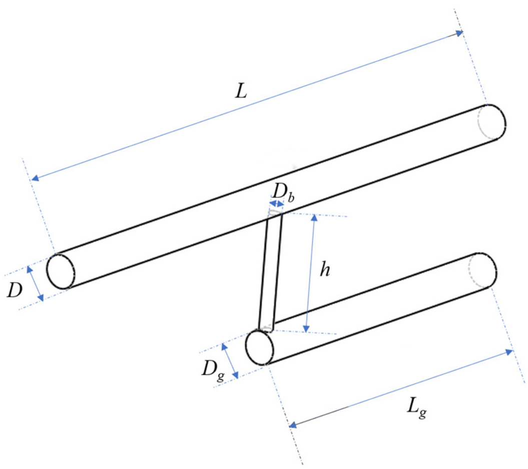

Figure 1. Configuration illustrated

2.3. Mathematical Model

To ensure simulation accuracy, the volumetric method was adopted for analyzing the T-tube separator process. Given the complexity of vertical branch pipes, main pipes, and their dynamic field variations one of the most intricate challenges a simplified approach was implemented. When using FLUENT software for simulations, three fundamental conservation laws must be strictly observed: mass conservation, momentum conservation, and energy conservation. For this study, the RNG *k-ε* model was selected as the turbulence model.

(1) conservation of mass, mass conservation

$$\frac{\partial(\rho \mathrm{u})}{\partial x}+\frac{\partial(\rho\upsilon)}{\partial y}=0$$

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In the formula, u denotes the flow velocity in the x-direction, while the corresponding value represents the flow velocity in the y-direction. The density of oil-water mixture is denoted by ρ , with ρ_i representing the density of the i component and α_i the volume fraction of the i phase.(2)(2)conservation of kinetic energy

$$\frac{\partial(\rho u \upsilon)}{\partial x}+\frac{\partial(\rho u \upsilon)}{\partial y}=\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+T_{\mathrm{u}}$$

$$\frac{\partial(\rho u \upsilon)}{\partial x}+\frac{\partial(\rho u \upsilon)}{\partial y}=\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+\rho g+T_{\upsilon}$$

$$T_{\upsilon}=\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)$$

$$T_{\mathrm{u}}=\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)$$

(3)Energy Conservation

$$\frac{\partial}{\partial x_i}(\rho u_i T)=\frac{\partial}{\partial x_i}\left[\left(\frac{\mu}{\mathrm{Pr}}+\frac{\mu_i}{\sigma_i}\right)\frac{\partial T}{\partial x_i}\right]$$

2.4. Grid Division

Fluent meshing divides the computational domain into numerous small subdomains to facilitate flow field simulation within each region. The significance of Fluent meshing lies in:

(1) Ensuring computational accuracy: Fluent calculates flow fields by discretizing the entire basin into fine mesh cells and solving the governing equations within each cell. Thus, the mesh resolution directly determines the accuracy—coarser meshes yield lower precision, while overly fine meshes waste computational resources. Proper meshing ensures both the accuracy and reliability of simulation results.

(2) Boosting computational efficiency: Fluent simulations involve extensive calculations, where excessive mesh cells increase computational load and degrade efficiency. Optimal meshing ensures both computational accuracy and efficient processing.

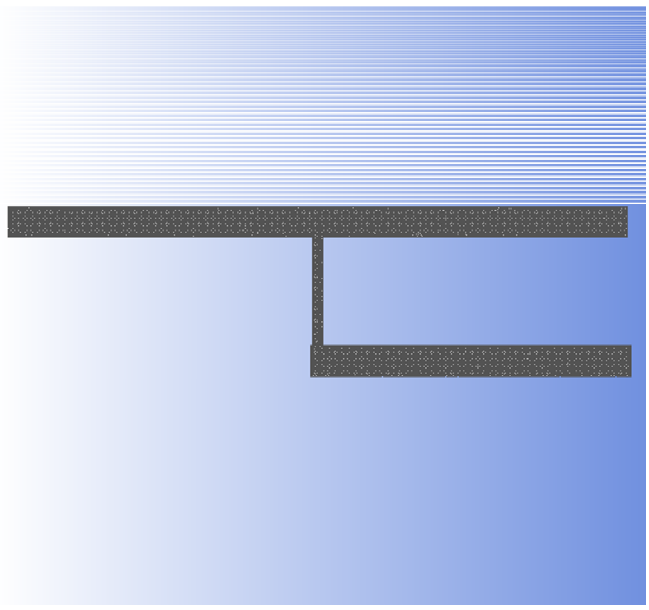


Figure 2. Grid schematic diagram

(3) Stability of simulation calculations: Uneven meshing or irregularly shaped/malformed mesh elements may cause computational instability or program crashes. Proper meshing ensures computational stability and enhances program reliability.

Therefore, this paper adopts the ICEM software for meshing, using an unstructured mesh with 670,000 elements, as shown in Figure 2.

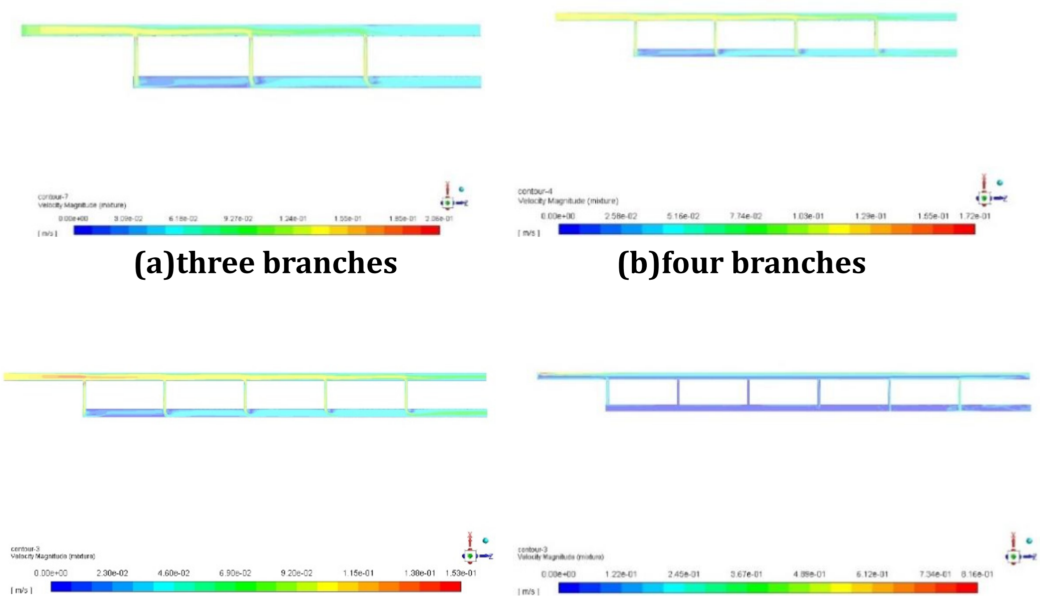
3. Study on Structure Optimization of T-tube Separator

Based on the analysis of flow field, the key structure of T-tube separator is optimized in this chapter. The research is carried out from the aspects of the number of branch tubes and the diameter of main tube, the flow process and separation efficiency are analyzed, and the influence of geometric parameters on the separation process is clarified.

3.1. Effect of the Number of Branch Ducts on the Speed of Fusion

In this section, the effect of the number of branch pipes on the separation performance of the T-type pipe separator is studied by changing the number of branch pipes (3, 4, 5, 6). The inlet operating parameters are similar to those in the previous chapter, with the inlet mixing velocity being 0.1 m s-1, the oil content being 5%, and the split ratio being 0.5.

Figure 3 illustrates the impact of branch pipe quantity on separation efficiency. The diagram shows that while the horizontal main pipe and branch pipes achieve thorough mixing before convergence, the flow velocity surges dramatically at the junction. Upon reaching the collector pipe, the mixture undergoes renewed thorough mixing. An increased number of branch pipes disperses the oil-water mixture into smaller flow units, enhancing contact opportunities and improving separation efficiency. However, excessive branch pipes also slow down flow velocity, which may hinder separation. As the number of branch pipes increases (e.g., three branches), three low-velocity zones emerge at their lower ends, forming relatively independent velocity regions. These low-velocity zones result from the combined effects of flow field characteristics and fluid properties within the pipes. The abrupt change in flow direction at the lower end of branch pipes generates vortices, leading to reduced velocity and the formation of low-velocity zones. Excessive branch pipes create more low-velocity zones, with their positions and quantities becoming more complex, resulting in relatively higher mixing levels.



(a)three branches (b)four branches

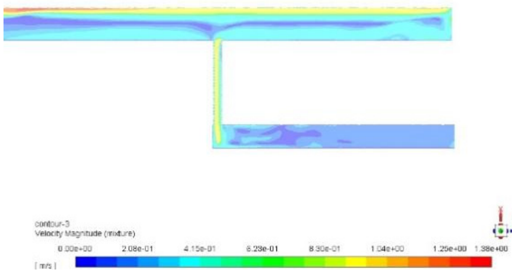
(c)Five branches (d)six branches

Figure 3. Influence of Branch Pipe Quantity on Matching Speed

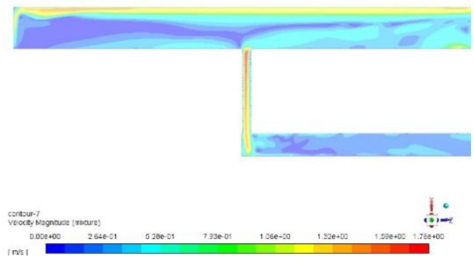
When the number of branch pipes is low, fluid flow becomes insufficient, resulting in uneven pressure and velocity distribution. Consequently, the velocity cloud diagram displays irregular cloud dots (in oil-water separation diagrams, these dots represent variously shaped, sized, and colored points that indicate microdroplets or bubbles in the mixture. The distinct velocity patterns caused by differences in flow velocity relative to surrounding fluid create point-like velocity distributions, representing the separated oil and water phases respectively. Observing the size, quantity, and distribution of these dots helps assess separation efficiency and identify trends in fluid properties). The distribution appears chaotic. As the number of branch pipes increases, fluid flow paths and velocity distribution become more rational. When the number of branch pipes reaches six, the cloud diagram exhibits a significantly different distribution pattern compared to three, four, or five branches, with a marked decrease in flow velocity that stabilizes.

3.2. Directed Diameter Optimization

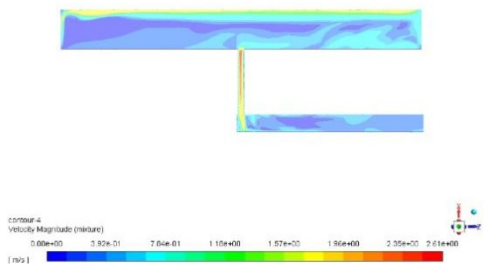
The figure illustrates how branch pipe length affects the velocity profile. As shown, larger pipe diameters result in lower merging velocities. This occurs because increased pipe diameter reduces fluid resistance, requiring less velocity to maintain stable flow rates a factor that impacts oil-water separation efficiency. The dark blue low-velocity zone appears when flow patterns shift from laminar to turbulent due to diameter and velocity changes. Turbulent flow exhibits uneven velocity distribution, creating high-velocity regions. Diameter variations also cause localized velocity spikes. Collectively, these dark blue zones likely indicate significant velocity gradients within the pipeline, which may compromise fluid stability and flow dynamics. This explains the low-velocity area observed at the main pipe's central axis.



(a)70mm



(b)90mm



(c)110mm

Figure 4. Effect of the Diameter of the Guide on the Speed of the Cloud

4. Conclusion

This study employs the RNG k-ε turbulence model and Eulerian multiphase flow model to investigate the flow characteristics and oil-water separation efficiency in T-tubes. Based on these findings, we optimized the number of branch pipes, horizontal pipe diameter, and branch pipe length of the T-tube, and analyzed how these structural parameters affect separation performance. The key conclusions are as follows: (1) Increasing the number of branch pipes and reducing the horizontal pipe diameter significantly enhances separation efficiency. Under the inlet conditions tested, configurations with 5 or 6 branch pipes demonstrated optimal

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separation performance. In practical engineering applications, the number of branch pipes should be adjusted according to varying inlet velocities, oil content, and split ratios.

(2) Increasing the horizontal pipe diameter slows down the liquid flow velocity. This slower flow prolongs the liquid's residence time in the pipeline, thereby reducing the oil-water separation efficiency. Moreover, the enlarged diameter decreases the contact area between the liquid and the pipe wall, diminishing both frictional and adhesive forces. Consequently, the driving force for oil-water separation is weakened, leading to a decline in separation efficiency.

(3) To enhance the efficiency of oil-water separation in horizontal pipelines, an appropriate pipe diameter should be selected. When the pipe diameter is smaller, better oil-water separation performance is achieved; when the pipe diameter is larger, additional measures should be implemented to improve separation efficiency, such as installing annular obstructions or increasing the degree of liquid turbulence.

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