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OIL-WATER TWO-PHASE FLOW INSIDE T-JUNCTION*

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Abstract: The oil / water two-phase flow inside T-junctions was numerically simulated with a 3-D two-fluid model, and the turbulence was described using the mixture k - ε model. Some experiments of oil / water flow inside a single T-junction were conducted in the laboratory. The results show that the separating performance of T-junction largely depends on the inlet volumetric fraction and flow patterns. A reasonable agreement is reached between the numerical simulation and the experiments for both the oil fraction distribution and the separation efficiency.

Key words: T-junction, two-phase flow, liquid / liquid separation, numerical simulation

1. Introduction

T-junctions shown in Fig.1 are very common within pipe networks in the petroleum industry. When two-phase flow encounters a T-junction, the phase maldistribution would inevitably take place between the run and the branch, exerting a profound effect on the flow control and processing facilities downstream [1]. On the other hand, petroleum extraction is now being shifted from onshore oilfields to offshore ones, and it is well known that current phase separators are usually very large in volume, which is not only very costly to build and place on the platforms, but also presents a great threat to the safe operation due to the existence of large inventory of flammable material. Consequently, numerous efforts have been made to develop a kind of multiphase separator both compact and highly - efficient in the recent years [2, 3]. The T-junction, as an efficient partial phase separator, can greatly reduce the processing load on the main separator. For example, a T-junction has been installed successfully in the chemical industry and used to partially separate the flashed products from a reactor [4].

In 1973, Oranje [5] reported that certain stations in a gas transmission network received dry gas whereas other stations received only condensate. An experiment was designed to investigate this phenomenon, and the results indicated that the split ratios are affected by several factors, including an under-pressure in the branch, the mass inertia of the liquid, the flow pattern upstream and the geometry of the T-junction itself. Since then, considerable researches have been conducted on the multiphase flow behavior inside T-junctions. A geometrical model was suggested by Azzopardi et al. [6], and later a flow pattern dependent model was proposed by Shoham et al. [7] to predict the flow splitting in a horizontal T-junction for the stratified wavy and annular flow patterns. For gas / liquid flow with low liquid holdup, a so-called "double stream model" was

Fig.1 T-junction in pipe network

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derived from the steady-state macroscopic mechanical energy balance to predict the liquid route preference [8]. Based on the equations of mass, momentum and energy balance, Dionissios [9] studied the dynamic separation of gas and liquid inside a T-junction with a horizontal run and a vertical branch. Adechy et al. [10] applied CFD techniques to compute the dispersed core flow simultaneously with the flow of the liquid film along the walls, in which the core is represented as a dispersed two-phase mixture and the liquid film modeled as a thin boundary layer. It was found that the predictions agreed well with the measurements within a certain range of phase split ratios.

A survey of the literatures shows that so far almost all efforts have been concentrated on gas / liquid flow inside T-junctions, compared with so limited work on the liquid / liquid two-phase flow. In 2006, the phase split of kerosene and water at a T-junction was investigated experimentally for the first time by Yang et al. [11], and a simplified model was proposed for the prediction of phase maldistribution. Besides, the splitting data of liquid / liquid two-phase flow at a horizontal T-junction was also measured [12]. In China, despite great efforts on oil-water flow inside single pipes [13, 14], the liquid-liquid flow inside T-junctions has received no attention until now.

As mentioned above, several models have been proposed to predict the flow behavior inside T-junctions, and nearly all the models are either wholly empirical or based on flow analysis still relying on empirical correlations, which renders the predictability of phase separation to be largely dependent on the specific experiments [15]. Thus, Lahey [16] argued that no completely satisfactory model exists for the prediction of phase separation in conduits of untested geometry and / or operation conditions. On the other hand, considerable advances have been made recently in simulating the multiphase flow inside complex geometrical structures. In the present study, therefore, the oil / water two-phase flow at a T-junction is numerically simulated to study the detailed phase distribution and splitting phenomena. Besides, to verify the numerical results, some experiments of oil / water flow inside a single T-junction are also conducted under different inlet conditions.

2. Numerical simulation

Several mathematical models have been proposed to simulate multiphase flow, of which the two-fluid model is the most accurate [17,18]. In Fluent, this model includes a set of momentum and continuity equations solved for each phase and the coupling between phases is achieved through the pressure and interphase exchanging coefficients. The governing equations are as follows.

According to the mass conservation law, the continuity equation is:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u}_k) = 0 \tag{1}$$

where

$$\sum_{k=1}^{N} \alpha_k = 1 \tag{2}$$

The conservation equation for the momentum can be expressed by

$$\frac{\partial}{\partial t}(\alpha_k \rho_k \boldsymbol{u}_k) + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u}_k \boldsymbol{u}_k) =$$

$$-\nabla(\alpha_k p) - \nabla \cdot \overline{\overline{\tau}}_k + \alpha_k \rho_k \boldsymbol{g} + \alpha_k \rho_k \cdot$$

$$\left(\boldsymbol{F}_k + \boldsymbol{F}_{lift,k} + \boldsymbol{F}_{vm,k}\right) + K_{kl}(\boldsymbol{u}_k - \boldsymbol{u}_l) \tag{3}$$

In case the particle diameter is relatively large, the following lift force must be taken into account:

$$F_{lift} = -0.5 \alpha_k \rho_k \left|\boldsymbol{u}_k - \boldsymbol{u}_l\right| \times (\nabla \times \boldsymbol{u}_l) \tag{4}$$

Due to the acceleration of the secondary phase to the primary phase, a virtual mass force on the particles should also be considered, defined by:

$$F_{vm} = \frac{1}{2} \alpha_k \rho_k \left(\frac{\mathrm{d}\boldsymbol{u}_l}{\mathrm{d}t} - \frac{\mathrm{d}\boldsymbol{u}_k}{\mathrm{d}t}\right)_l \tag{5}$$

The exchange coefficient K_{kl} for oil / water two-phase flow can be written in the following general form:

$$K_{kl} = \frac{\alpha_k (\alpha_k \rho_k + \alpha_l \rho_l) f}{\tau_{kl}} \tag{6}$$

herein, τ_{kl} is the particulate relaxation time and f the drag function, defined as:

$$\tau_{kl} = \frac{(\alpha_k \rho_k + \alpha_l \rho_l)\left(\frac{d_k + d_l}{2}\right)^2}{18(\alpha_k \mu_k + \alpha_l \mu_l)} \tag{7}$$

$$f = \frac{C_D Re}{24} \quad (8)$$

$$C_D = \frac{24\left(1+0.15Re^{0.687}\right)}{Re}\ ,\ Re \le 1000 \quad (9a)$$

$$C_D = 0.44\ ,\ Re > 1000 \quad (9b)$$

$$Re = \frac{\rho_k \left| \boldsymbol{u}_k - \boldsymbol{u}_l \right| d_k}{\mu_k} \quad (10)$$

Currently several types of turbulence models can be applied to describe the effects of turbulent fluctuations of velocities and scalar quantities in multiphase flow, of which the mixture k-ε model is applicable in case the phasic density ratio close to unit. In this model, k and ε equations are as follows:

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla \cdot (\rho_m \boldsymbol{u}_m k) = \nabla \cdot \left(\frac{\mu_{t,m}}{\sigma_k} \nabla k \right) + G_{k,m} - \rho_m \varepsilon \quad (11)$$

$$\frac{\partial}{\partial t}(\rho_m \varepsilon) + \nabla \cdot (\rho_m \boldsymbol{u}_m \varepsilon) = \nabla \cdot \left(\frac{\mu_{t,m}}{\sigma_\varepsilon} \nabla \varepsilon \right) + \frac{\varepsilon}{k}(C_{1\varepsilon} G_{k,m} - C_{2\varepsilon} \rho_m \varepsilon) \quad (12)$$

where, the mixture density ρ_m and the mixture velocity $\boldsymbol{u}_m$ are defined as

$$\rho_m = \sum_{k=1}^{N} \alpha_k \rho_k \quad (13)$$

$$\boldsymbol{u}_m = \frac{\sum_{k=1}^{N} \alpha_k \rho_k \boldsymbol{u}_k}{\sum_{k=1}^{N} \alpha_k \rho_k} \quad (14)$$

The turbulent viscosity μ_t and the production of turbulence kinetic energy $G_{k,m}$ can be computed from:

$$\mu_{t,m} = \rho_m C_\mu \frac{k^2}{\varepsilon} \quad (15)$$

$$G_{k,m} = \mu_{t,m} \left[\nabla \boldsymbol{u}_m + \left(\nabla \boldsymbol{u}_m \right)^{\mathrm{T}} \right] : \nabla \boldsymbol{u}_m \quad (16)$$

The geometrical model used in the numerical simulation is given in Fig.2, in which the angle between the main pipe and the branch is 90°. The pipe diameter is 0.05 m and each pipe segment 1.0 m long. During the grid generation, the mesh density is gradually increased from the pipe center to the wall as the velocity gradient is generally very large in the region adjacent to the pipe wall.

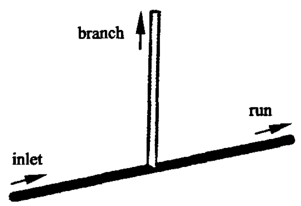


Fig.2 Geometrical model in the numerical simulation

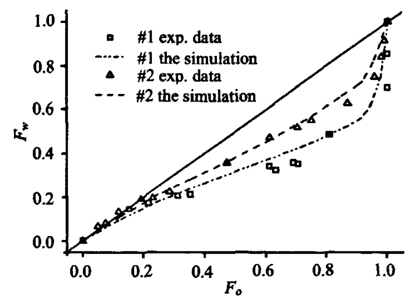


Fig.3 Comparison between numerical results and experimental data

At the inlet, uniform profiles for all the dependent variables are employed, and the velocity is perpendicular to the inlet cross-section. The outlet boundary conditions are set according to the practical experimental conditions. Besides, a no-slip boundary condition is imposed on the pipe wall, which means both the velocity and the turbulence kinetic energy are zero.

To verify the above model, the oil / water two-phase flow inside a horizontal T-junction is numerically simulated, and the results are compared with the experimental data obtained by Yang et al. [10]. In run #1, the mixture velocity is $v = 0.55\ \mathrm{m/s}$ and the oil volumetric fraction $\alpha = 27.3\%$, and in run #2, $v = 0.86\ \mathrm{m/s}$ and $\alpha = 25.6\%$. Figure 3 compares the predicted and measured split ratios of kerosene and water inside the horizontal T-junction. In view of the inherent complexity of liquid / liquid flow at the intersection, the agreement between the simulation and experimental data is satisfactory.

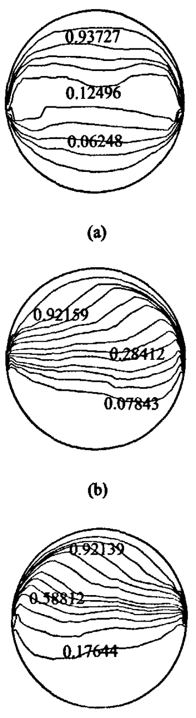


Fig.4 Distribution of oil volume fraction and streamline at the cross-section

The cross-sectional distribution of oil phase at the inlet, the run and the branch is given in Fig.4, where the cross-sections are 3 times the pipe diameter away from the intersection center. As can be seen from Fig. 4(a), two layers of oil and water appear at the upper and lower parts respectively with mixture dominating at the interface, which can be classified as ST and MI (stratified flow with mixture at the interface) and is in accordance with the actual flow pattern in the experiments. In Fig.4(b), the oil is distributed in the upper left part under centrifugal force in the branch due to the abrupt turn of flow direction. Besides, the cross-sectional oil volume fraction also changes in the run resulted from the disturbance at the intersection. A further analysis indicates that the cross-sectional phase distribution would stay unchanged at a distance of about 8 times the pipe diameter downstream.

3. Results and discussion

An experimental system was established at the Laboratory of Applied Fluid Dynamics in CAS, and some experiments of oil / water two-phase flow inside T-junction were conducted. The T-junction in Fig.5 is made of plexiglass to enable visual observation of flow patterns. Totally six vertical pipes are installed, and the present study is, however, only limited to the maldistribution oil / water flow at a single T-junction. The pipes are all 0.05 m in diameter and each pipe segment 1.0 m in length. In the experiments, the oil is mixed with water at a predetermined ratio inside the jet pump, and then the oil / water mixture would be split at the T-junction and enter into the mixture tanks from the exits of the run and the branch. Finally oil and water would flow back to oil tank and water tank respectively after gravitational settlement.

The LP-14 white oil and deionized water are used in the experiments, and the physical properties under test conditions are as follows: ρ_o=836.0kg/m^3, μ_o=0.031kg/m·s, ρ_w=998.0kg/m^3, μ_w=0.001kg/m·s. The oil volume fraction at the inlet ranges from 10.0 to 90.0 percent, and the mixture velocity 0 m/s-1.5 m/s. In this study, the mixture velocity at the inlet is controlled between 0.45 m/s and 0.80 m/s, and the oil volume fraction 20.0 to 45.0 percent. Two main flow patterns, including stratified / wavy flow and dispersed flow, occur in the experiments. Three typical runs of experimental data are listed in Table 1.

In the experiments, significant splitting phenomenon occurs at the T-junction when the inlet oil / water flow pattern is ST and MI, while the phase maldistribution is relatively unremarkable for DS. In other words, the separating performance of a single T-junction is very sensitive to the inlet flow patterns, which is unexpected in the practical engineering applications. To conquer this problem, it may be appropriate to make the oil / water mixture split continuously by installing several vertical branches at a fixed interval along the horizontal pipe, as shown in Fig.5.

In the numerical simulation, the boundary conditions are set according to the actual experimental conditions, of which the pressure at the exits of the run and the branch is the atmospheric pressure. Take run 1# as an example, the flow pattern at the inlet is

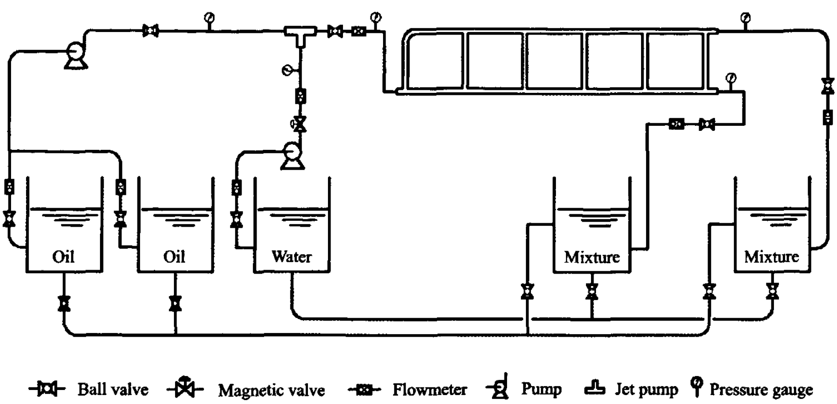
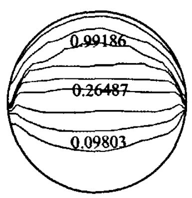
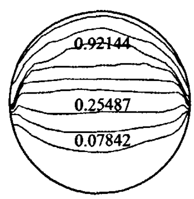


Fig.5 Experimental system for oil / water two-phase flow in T-junction

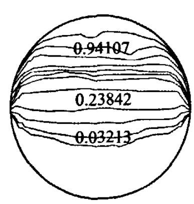
Fig.6 Oil / water flow pattern in the inlet (ST and MI)



(a)



(b)



(c)

Fig.7 Cross-section oil volumetric fraction in the run

similar to that in Fig.4 and in good agreement with the actual flow pattern shown in Fig.6, where the water is red after being mixed with potassium permanganate.

Figure 7 shows the cross-sectional distribution of oil volume fraction at a distance of 3, 6 and 9 times the pipe diameter downstream from the intersection center. It can be seen that the layers of oil and water gradually become thicker as the oil / water mixture continues to flow along the pipe. The cross-sectional phase distribution keeps symmetric along the vertical centerline, which is very different from those in Fig.4. This difference mainly owes to the combined influence of the gravitational force and the centrifugal one. As the flow continues in the pipe, water and oil would gradually separate under the gravitational force, and a further analysis indicates that the phase distribution become steady at the location about 10 times the pipe diameter downstream.

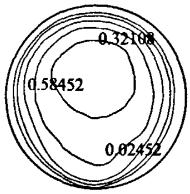
The distribution of oil volume fraction in the branch is shown in Fig.8, and the distances between the cross-section and the intersection center are the same as those in Fig.7. When the oil / water mixture enters into the branch, the oil tends to be closer to the inlet due to its lower mass inertia. As the oil / water mixture continues to flow upward, the disturbance at the intersection gradually declines, and besides, the gravitational force in this case is symmetric for both the phases, thus the phases tend to become more and more uniformly distributed from cross-section (a) to (c).

On the other hand, the oil concentration gradually becomes higher as the oil / water mixture flows upward. As can be seen in (c), pure water appears in the region adjacent to the pipe wall, which agrees well with experimental observation given in Fig.9.

Table 1 three typical experimental runs

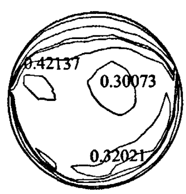
Run	Flow pattern	Mixture velocity in the inlet	Oil volume fraction in the inlet	Mixture velocity in the branch	Oil volume fraction in the branch
1#	ST and MI	0.480 m/s	0.2656	0.242 m/s	0.3916
2#	St and MI	0.521 m/s	0.2997	0.279 m/s	0.4007
3#	DS	0.728 m/s	0.2182	0.356 m/s	0.2341

Note: ST and MI represents stratified flow with mixture at the interface, and DS the dispersed flow.



(a)

(b)



(c)

Fig.8 Cross-section oil volumetric fraction in the branch

Fig.9 Flow pattern in the branch

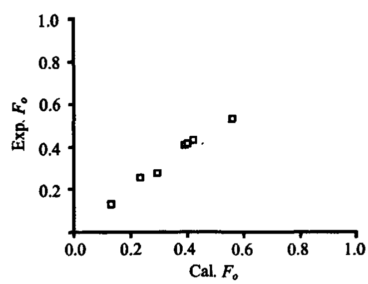


Fig.10 Comparison between numerical results and experiment data of oil split ratio

In Fig.10, a good agreement exists between the simulated phase split ratio and the experimental data, indicating that the numerical methods is able to predict the splitting phenomena of oil / water flow at both the horizontal and vertical T-junctions. Therefore, the validated numerical simulation can be applied to study the influences of various parameters on splitting phenomenon, and to optimize the geometrical structure of T-junction to achieve higher separation efficiency.

4. Conclusions

The oil / water two-phase flow in the T-junction has been investigated both numerically and experimentally in the present study. The main conclusions are as follows:

The two-fluid model, together with the mixture k-ε turbulence model, can be used to numerically simulate the oil / water two-phase flow in the T-junction. Both the distribution and the phase split ratios in the numerical simulation are in good agreement with the experimental results.

The experiments show that the separating performance of a single T-junction is very sensitive to the flow patterns in the inlet. For STandMI, the oil and water would be separated well at the intersection, while unremarkable splitting phenomenon occurs in case of DS.

To meet the requirements of practical engineering applications, experiments on oil / water flow in T-junctions with several branches will be conducted in the near future to investigate the separating efficiency, flow rate, and flow pattern under different inlet conditions.

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