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A Review of Progress in Oil-Water Two-Phase Flow Research

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Abstract

This paper summarises the current state of research on oil-water two-phase flow, covering flow pattern classification, experimental studies, and model calculations. Common flow patterns and their influencing factors are introduced, and the conversion of different flow types is analyzed. The characteristics and results of various experimental devices and methods are presented, as well as the application of multiphase flow models and solution methods in practical calculations. The applications and challenges of oil-water two-phase flow in the petroleum industry and other fields are discussed for subsequent research.

Keywords

Oil-water Two-phase Flow; Flow Pattern Classification; Experimental Research; Model Calculations.

1. Introduction

In the process of oil production and transport, oil and water two-phase flow is a common phenomenon, because crude oil and water are two incompatible substances, resulting in oil and water two-phase flow there are complex flow characteristics [1]. The research of liquid-liquid two-phase flow originated in the early twentieth century, due to the immaturity of the research means at that time, the experimental equipment was backward, only the liquid-liquid two-phase flow of the liquid-liquid two-phase flow of the malefactor to carry out a relatively rough flow state research. Until the nineties of the twentieth century, due to the problem of liquid-liquid mixing of crude oil extraction in the petroleum industry, the Western developed countries, led by the United States, the United Kingdom, Israel, and France, carried out the research work of liquid-liquid two-phase rheological properties [2]. In recent years, due to the large number of China's oil pipeline production, the pipeline drop leads to a large number of oil pipeline production in the initial period of the undulating low-lying areas have a large amount of water, the internal corrosion is more serious so that some scholars will oil-water two-phase flow as a liquid-liquid two-phase flow of the focus of the research. At present, domestic and foreign liquid-liquid two-phase flow has a certain theoretical and experimental research basis. The main research content includes experimental analysis and process calculation model establishment. Many scholars at home and abroad have analyzed the two-phase flow pattern of oil and water using experimental research and calculated the friction pressure drop and water content. This study aims to provide an overview of the main research results on the flow characteristics of oil and water two-phase flow in pipelines and to provide an outlook for future research directions.

2. Oil-water Two-phase Flow Pattern

In the characterization of oil-water two-phase pipe flow, it is necessary to identify the flow pattern. In the process of oilfield production, especially in the middle and late stages of high-water content and low fluid production, oil-water two-phase flow is one of the very typical multiphase flows.

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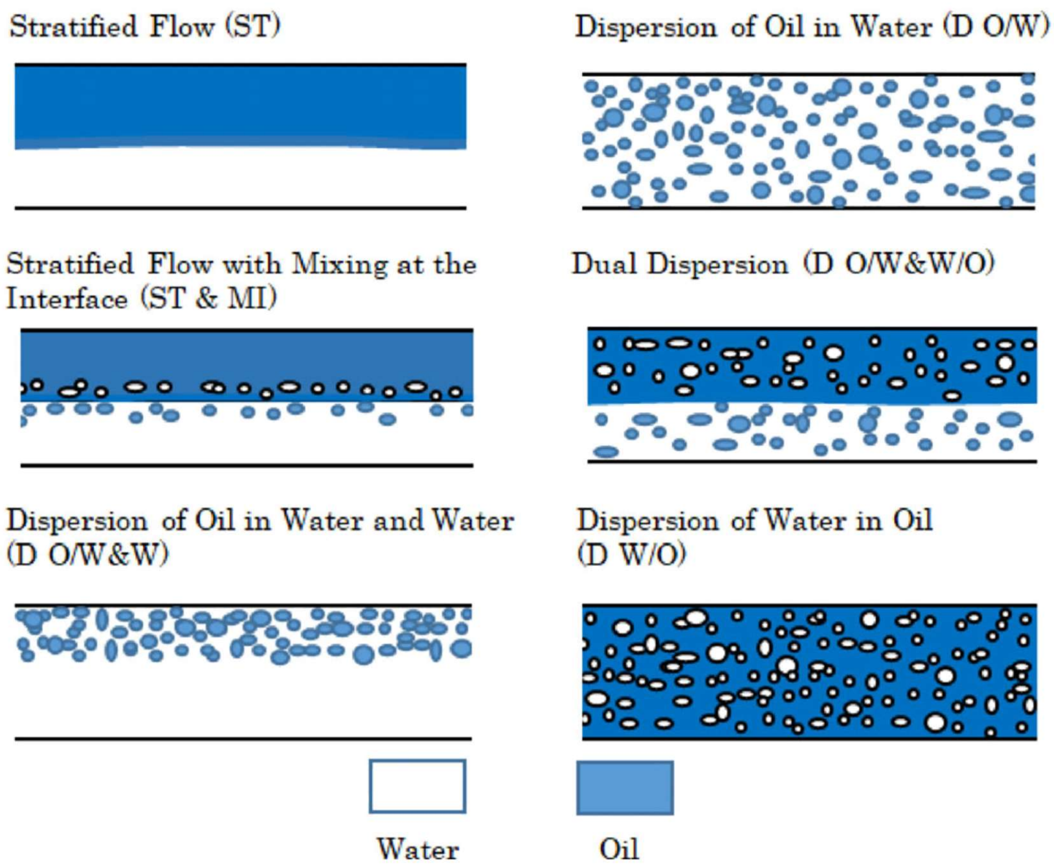

Fig. 1 Schematic diagram of oil-water two-phase flow pattern in a horizontal pipe

Terrarello [3] classified the horizontal pipe oil-water two-phase flow patterns into two main categories, i.e., separated flow patterns and dispersed flow patterns

(1) Separated flow patterns. This broad category includes stratified flow patterns as well as stratified flow patterns with slight mixing at the phase interface.

(2) Dispersed flow type. The total includes water as a continuous phase and oil as a constant phase.

Which can be specifically divided into the following parts, corresponding to the flow pattern in Figure 1:

(1) Stratified Flow (ST)

The fluid in the flow type of each stratified flow, usually water in the lower part of the pipeline, oil in the upper part of the pipeline, the existence of waves on the phase interface waves exist at the phase interface.

(2) Stratified Flow with mixing at the interface (ST&MI)

The flow is mostly laminar, but there is a mixing region at the interface between the two phases. The mixing region at the interface is critical. However, the mixing area is very narrow, except for the mixing area, there is no mixing phenomenon in other areas, the top and bottom of the pipeline are pure substances.

(3) Dispersion of oil in water and water (DO/W&W)

The water layer is distributed throughout the whole pipeline, there is a layer of water without a crude oil dispersed phase at the bottom of the pipeline, and the upper layer of the pipeline is crude oil droplets, and the upper layer of the pipeline is crude oil droplets. The upper layer of the pipeline is a small droplet of crude oil dispersed in the aqueous phase liquid flow

(4) Oil in water emulsion (O/W)

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The flow type for the entire pipeline is small droplets of crude oil dispersed in the aqueous phase, that is, completely water-in-oil flow type, such as

(5) Water in oil emulsion (W/O)

The flow type in the oil is a continuous phase, water forms small droplets completely dispersed in the oil phase, and the whole pipeline are water-in-oil type.

(6) Dispersions of water in oil and oil in water (DO/W&WO)

The flow pattern has two flow layers, two flow layers are distributed throughout the pipeline, the upper layer of the pipeline for the continuous water-in-oil phase layer. The lower layer of the pipe is a continuous oil-in-water layer.

Flores [4] investigated the conditions of an inclined pipe with an internal diameter of 50.8 mm and a length of 381 mm using mineral oil and water as media for inclinations of 45°, 60°, and 75°. He divided the flow pattern of the ascending inclined pipe into six types and classified them into two major categories: oil continuous phase flow type and water continuous phase flow type.

(1) Water as a continuous phase. Including oil droplet dispersion and water layer with local reflux flow type, oil droplet dispersion and water layer for the proposed section plugging flow type, oil droplet dispersion and water layer isotropic flow type, oil droplet uniform dispersion, and transition flow.

(2) The oil is a continuous phase. These include droplet-dispersed flow patterns and droplet uniformly dispersed flow patterns. He believes that the difference between the flow pattern of inclined pipe and horizontal pipe and vertical pipe is mainly affected by the inclination angle. When the oil-water flow velocity is small, there will be oil droplet dispersion and the water layer has a local countercurrent flow pattern, due to the small momentum of the water flow at this time, it is not enough to offset the downward force of gravity, which produces the phenomenon of local reflux. If the water phase velocity increases, the continuous oil droplet dispersion region will be interrupted by course block distribution, if the momentum of the water is still unable to overcome the effect of gravity, the local countercurrent situation will continue to exist, thus forming the oil droplet dispersion and the water layer for the proposed section of the plug flow type. Further, increase in the water-phase flow velocity, there will be oil droplets dispersed and the water layer isotropic flow flow type, this time the local countercurrent phenomenon is eliminated. With further increase in the water phase velocity, the dispersed oil droplet particle size will gradually become smaller and uniformly distributed in the water phase, at this time the oil droplet dispersed flow type. A transitional flow pattern is in the oil continuous phase and water continuous phase between a flow pattern.

Lum [5] observed the flow patterns of two streams of oil and water in a stainless steel test pipe with a diameter of 38 mm in the ascending (+5°, +10°) and descending (-5°) pipes. He observed four flow patterns: (1) stratified wavy flow. He observed that the interface of the stratified flow was more fluctuating and the shape of the interface wave was more irregular in the line with an inclination angle of +10° compared to the +5° line. (2) Segmental plug flow. This type of flow occurs in the oil content is relatively small (10% -30%), and is a time-dependent flow pattern, every certain time in the pipeline at the top of the length of a few diameters of the oil segment plug. (3) Three-layer flow. When the oil content increases to 60%-80%, a three-layer flow occurs. Oil droplets collect on the dividing surface of the two phases. (4) Fully dispersed flow.

Wu [6]carried out an experimental study on oil-water two-phase flow patterns, which was completed in a horizontal pipeline with a length of 20 m and an inner diameter of 40 mm. Seven oil-water two-phase flow patterns were identified under the experimental conditions, i.e., stratified flow (ST), three-layer flow (3L), oil droplet dispersed flow (ODST), fully dispersed mixed flow (M), elastic flow (SL), oil-droplet dispersed stratified flow (2L), annular flow (A), etc. The results are shown in the following table. (2L), and annular flow (A). In addition, the

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experimental results show that the physical properties of the oil-water two-phase, the apparent flow rate, and the pipe size are the fundamental factors for the transformation of the stratified flow type to the non-stratified flow type in oil-water two-phase flow. The Kutadelaze number is obtained by developing a force analysis of the oil and water phases to characterize the equilibrium effect of each force.

3. Experimental Study of Two-phase Oil-water Flow

Many scholars have carried out experiments on a single pipe diameter, multi-inclination experimental frame with diesel fuel as the experimental medium for a variety of oil-phase flow rates and water-phase flow rates, and have studied the geometric parameters of the experimental frame and the effects of the two-phase flow rates on the flow pattern, water content, pressure drop.

Angeli [7] used the experimental frame with a 24.3 mm pipe diameter, 9.7 m experimental section length, and 0°, 45°, 90° inclination angle to study the change rule of flow pattern, phase distribution, and water content in the pipe when the flow rate of the oil-water mixture is 0.2-3.9 m/s, and they conclude that in the transition period of the two flow patterns, the three-layer flow will appear in the pipe. However, the experiment involves a limited inclination, and the span between adjacent inclinations is large, not to form a more complete flow pattern mapping.

Flores [4] investigated various flow patterns at two-phase apparent flow velocities of 0.045-1.27 m/s using an experimental frame with an inner diameter of 50.8 mm, a length of 15.3 m, and inclination angles of 90°, 75°, 60°, and 45°. They found there is no slug flow above the inclination angle of 33°. A flow transition model is proposed and compared with experiments. The flow transition is determined by the breakup and aggregation of droplets. Except for the VFD and O/W, the rest of the water-phase-dominated flow patterns show severe slipping. The experiment is important for the derivation of flow pattern transition models for other operating conditions, but the experiment does not take into account the effect of pipe diameter on the flow pattern and therefore has some limitations.

Atmaca [8] used an experimental stand with a pipe diameter of 50.8 mm, a length of 21.1 m, upward inclination angles of 0°, 1°, 2°, 5° and downward inclination angles of 1°, 2°, 5, using diesel fuel and water as the media, to The pressure drop, water content, and flow pattern transition law of the two-phase apparent flow rate of 0.025-1.75 ms were investigated, and the results obtained from the experiment were compared with the model to prove that it is a gradual process from laminar to dispersed flow. The research idea of this experiment is of great significance, but the inclination angle of this experimental frame is small, and the results obtained have some limitations.

Premanadhan [9] experimentally analyzed the effect of different oil viscosities (30 cP and 300 cP) on the distribution of flow pattern and pressure drop in oil-water two-phase pipe flow with a pipe diameter of 27.86 mm. The results show that the apparent flow velocity is lower for heavy oil than for light oil when the transition of flow pattern occurs. The transition point of light oil occurs earlier than that of heavy oil.

Lyu [10] studied the flow structures, droplet sizes, and viscosities of three different crude oils with different densities and viscosities, and experimentally analyzed the flow characteristics of water-in-oil dispersed flow. By analyzing the pressure gradient of three different crude oils at different flow rates, it was found that the pressure drop showed a trend of increasing and then decreasing with the increase in water content. By analyzing the effect of temperature on the pressure gradient of three different crude oils at different flow rates, it was found that the pressure drop of the three crude oils decreased with the increase in temperature. By analyzing the flow characteristics of the crude oils, such as viscosity, water content, mixing speed, and temperature, the effects on droplet size were investigated. The effects on apparent viscosity were investigated by analyzing the flow characteristics of crude oils at different mixing speeds, water contents, and temperatures. The viscosities at different mixing speeds were investigated, and it was found that the apparent viscosity increased with the increase of interfacial area concentration at different mixing speeds. A viscosity model was established, and the experimentally measured viscosities were compared with the predicted viscosities, and the results showed that the viscosity model had a high accuracy.

Vielmal [11] used a horizontal experimental frame with a pipe diameter of 50.8mm and a length of 21.13m to carry out experiments with mineral oil and tap water as the medium and fitted the pressure drop, phase fraction, and the droplet size as a function of the change in flow pattern. However, there is a certain gap between the experimental medium and the long-distance pipeline medium, and the experiments do not focus on quantitatively characterizing the flow pattern change rule of liquid-liquid two-phase flow in inclined pipelines.

Ali Ebrahimi-Mamaghani [12] predicted the flow pattern and water content at flow velocities of 0.1-1m/s using an experimental frame consisting of a vertical pipe with a diameter of 50.8mm and a slightly downward-sloping pipe. They concluded that vertical pipelines have only core annular flow and the pressure drop increases with the increase of oil viscosity, in addition, the oil viscosity has little effect on the flow pattern and water content. However, in long-distance pipelines, vertical pipelines rarely appear, but are mostly inclined pipelines, and the experiment involves fewer inclinations without forming flow pattern maps.

Hanafzadeh [13] investigated the effect of inclination angle on the pressure drop of two-phase flow at oil-phase flow rates of 0.29~2.35 m/s, and water-phase flow rates of 0.5~3.21 m/s using an experimental frame with an inner diameter of 20 mm, a length of 6 m, and upward inclination angles of 0°, 5°15°, 30°, and 45°, and downward inclination angles of 5°, 15°, 30°, and 45°. They concluded that there is a pressure drop peak at high flow rates, and in addition, it is easy to have an opposite rotation when the inlet water content is higher at -30°~-45° than other inclinations, as well as the two-phase friction factor, is smaller than that of the single-phase. The liquid-liquid dispersion can be used to calculate the pressure drop of the homogeneous-phase model. The experimental inclination angle is carefully divided, but the study does not focus on the flow pattern.

Xu [14] investigated the movement characteristics of water under the shear action of oil flow in a horizontal pipe with an inner diameter of 50 mm and upward inclined pipes with inclination angles of 1, 5, and 10°. It was found that when the apparent oil velocity, the inclination angle of the experimental pipe, and the height of the dimensionless water phase gradually increased, the flow pattern of water in the experimental pipe began to change from smooth laminar flow to wavy laminar flow, and liquid droplet laminar flow. Based on Froude's similarity criterion, the critical apparent oil velocities were predicted for the upward inclination angle of the pipe of 10° and the pipe diameters of 60, 70, and 80 mm, so that all the water would enter the upward inclined experimental pipe section, and compared with the experimental data, the accuracy of the prediction of critical apparent oil velocities for the upward inclination of all the water into the experimental pipe section based on the Froude's similarity criterion was confirmed, and the critical apparent oil velocities for the drainage of all the water into the upward inclined experimental pipe section were predicted for the pipe diameter of 489 mm. Then, the critical apparent oil velocity of 1.60m/s was predicted for the pipe with an inner diameter of 489mm to make all the water in the pipe discharged.

4. Modelling of Pressure Drop in Oil-water Two-phase Pipe Flow

The pressure drop model and its calculation of oil-water two-phase pipe flow is an important content of oil-water two-phase flow and oil, gas, and water multiphase flow research, which is of great significance for the design and operation management of multiphase flow pipelines in

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the oil field. Due to the complexity of the oil-water two-phase flow, different scholars have given the pressure drop model applicable to different situations.

In 1966, Charles [15] applied the L-M formula for pressure drop prediction in gas-liquid two-phase flow directly to oil-water two-phase flow, which had a large deviation. Theissing [16] modified the formula in 1980 to make it suitable for predicting the pressure drop in both oil-water and gas-liquid two-phase. Stapelberg [17] also investigated the L-M formula and pointed out that it is not possible to predict the pressure drop in all flow patterns using a single empirical formula.

Elspeth [18] proposed a pressure drop model for laminar flow without interphase slip, ignoring the interphase slip avoids solving the nonlinear equations, but it also increases the prediction error. Taitel&Dukler pressure drop model considers oil and water as separate continuous media, and empirical equations are used to calculate the drag coefficients between the fluid interface and the pipe wall, i.e., the two-fluid model. Kuban [19] derived a one-dimensional no-slip model based on the above model, which is consistent with the experimental results of laminar flow.

Vedapui [20] proposed a three-layer physical model of oil-mixture-water to describe the oil-water distribution in oil-water two-phase flow when studying the height of the water layer in the oil-water two-phase separation flow pattern. In 2001, Shi [21] proposed a four-layer separation model for calculating the pressure drop based on the three-layer separation flow concept, which considered not only the oil layer and the water layer but also the water-in-oil and water-in-oil layers. The model The predicted results are in good agreement with the experimental data.

Gao [22] numerically simulated the oil-water two-phase stratified flow in a horizontal pipe using a modified VOF model, and also referred to the CSF model of Brackbill et al. to take into account the effect of the surface stress, which yielded the values of the pressure drop, the inter-phase slip, and the in-situ phase fraction in the oil-water two-phase stratified flow.

For oil-water two-phase dispersed flow, a homogeneous flow model is generally used to predict the pressure drop. The homogeneous flow model regards the oil-water two-phase mixture as a uniform medium, ignores the relative velocity between the two phases, and calculates the pressure drop of the two-phase flow by the single-phase flow pressure drop equation. When the homogeneous flow model is used to predict the pressure drop of dispersed flow, the key lies in how to accurately calculate the effective viscosity of the oil-water two-phase mixture. Different effective viscosity models have been given by different scholars.

In 1906, Einstein [23] obtained a viscosity model for rigid spherical suspensions by theoretical derivation, and Brinkman [24] proposed a viscosity correlation equation for oil-water emulsions based on Einstein's correlation equation. In addition, many scholars have modified Einstein's viscosity equation to derive a series of empirical equations for effective viscosity.

Scholars [25-27] proposed different forms of effective viscosity models including only water content, respectively. Thereafter, many scholars [28-31] proposed different effective viscosity models by introducing the influencing factors such as oil-water interfacial tension, temperature, degree of mixing, effective medium, and effective volumetric concentration, respectively.

5. Summary

The characterization of oil-water two-phase pipe flow plays an important role in many fields such as petroleum engineering and chemical engineering. The study of the characteristics of oil-water two-phase pipe flow can be divided into two methods: experimental study and numerical simulation. In the study of the characteristics of oil-water two-phase pipe flow, it is necessary to identify the flow pattern. Scholars at home and abroad have carried out a large number of experimental and theoretical studies on oil-water two-phase flow and found that the

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flow pattern of oil-water two-phase flow is closely related to the fluid properties, pipeline conditions, operating pressure, etc., and each flow pattern has unique flow characteristics. With the development of visual experimental devices and their use, researchers can clearly and accurately observe the flow pattern changes during the oil-water two-phase pipe flow, which helps researchers better understand and study the flow characteristics of oil-water two-phase pipe flow. The experimental data measured in the experimental study can also provide data reference for the model calculation, and the model calculation study can compare the calculated values of the model with the experimental data to verify the accuracy of the model and optimize the model. With the development of model calculation, the flow characteristics of oil-water two-phase flow can be more accurately captured and described in the future by introducing advanced measurement tools. The combination of experimental research and model calculation research will provide a more accurate reference basis for oil-water two-phase pipe flow in engineering applications.

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