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Research on the Flow Characteristics and Collection Optimization of Two-Phase Flow of Heavy Oil and Hot Water

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Abstract

As an important part of petroleum resources, heavy oil faces the problems of high flow resistance and high energy consumption in the process of gathering and transportation due to its high viscosity and high density characteristics. This paper focuses on the flow characteristics of heavy oil hot water two-phase flow, systematically sorts out the basic theory, experiment and simulation research methods of oil-water two-phase rheological characteristics, and focuses on the influencing factors of reversed-phase points, viscosity prediction models and pressure drop and temperature drop characteristics, aiming to provide theoretical support for the optimization of heavy oil gathering and transportation process. The results show that moisture content, temperature and flow rate are the key parameters affecting the characteristics of two-phase flow, and the combination of experiments and numerical simulation is an effective means to reveal the flow law, and the application of intelligent prediction model provides a new path for the optimization of the gathering and transportation system.

Keywords

Heavy Oil; Hot Water Two-Phase Flow; Rheological Properties; Inverting Point; Pressure Drop; Temperature Drop.

1. Introduction

The viscosity of heavy oil is high at room temperature, resulting in significant friction with the pipeline walls. If direct transportation is carried out at room temperature, it may easily lead to excessively high wellhead back pressure, potentially exceeding the pipeline's design pressure and causing system shutdowns. As global energy demand increases, the effective development and utilization of heavy oil resources have become increasingly important. Researchers in various countries are continuously exploring economically viable and reliable transportation technologies. Currently, the mainstream methods for transporting heavy oil include heated transportation[1], diluted transportation[2], emulsified viscosity reduction[3], and water-assisted transportation[4], among which water-assisted transportation is widely used due to its low cost and ease of operation. The two-phase flow system formed by heavy oil and water exhibits complex rheological characteristics, and its flow pattern transitions, phase inversion phenomena, viscosity variations, and pressure drop and temperature drop patterns directly affect transportation efficiency. Thus, an in-depth study of the flow characteristics of hot water two-phase flow in heavy oil is of significant importance for optimizing transportation processes and reducing energy consumption.

2. Rheological Properties of Oil-Water Two-Phase Flow

The term "phase" in multiphase flow research has dual meanings: from a thermodynamic perspective, it refers to the states of matter such as gas, solid, and liquid; from a mechanical perspective, it refers to a group of particles with identical characteristics such as velocity and temperature [5]. The mixed flow of heavy oil and water falls into the category of two-phase flow

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regardless of either definition. The rheological properties of heavy oil exhibit characteristics of non-Newtonian fluids. The relationship between resistance and deformation during its flow does not follow Darcy's law or Newton's law of internal friction. This is attributed to the large amount of resins and asphaltenes in heavy oil, which result in high viscosity, poor fluidity during transportation, and issues such as low single-well production and low cumulative oil-gas ratio.

In the early 20th century, the United States took the lead in conducting research on rheology, initially focusing on Newtonian fluids. With the development of the petroleum industry, research on oil-water two-phase flow gradually gained attention. Rheological research in China began with the construction of the first waxy crude hot oil pipeline in Yumen Oilfield in 1944. The challenges in transporting high-pour-point crude oil drove the initiation of domestic research on oil-water two-phase flow. Through experiments on oil-water two-phase flow in horizontal pipelines, Charles et al. adjusted the oil phase density to 998 kg/m^3 and viscosity to 16.8 mPa·s by adding carbon tetrachloride to the oil. Under the conditions of a pipe diameter of 26 mm and a temperature of 20°C, they observed various flow patterns, including slug flow and bubble flow with oil as the dispersed phase, and mist flow and plug flow with water as the dispersed phase. This revealed the complexity and variability of oil-water two-phase flow patterns, laying the foundation for subsequent research.

3. Experimental and Simulation Studies on Oil-Water Two-Phase Flow

3.1. Experimental Research Methods

Experimental research is a fundamental means to explore the characteristics of oil-water two-phase flow. Wu Tiejun [6] et al. used a horizontal plexiglass pipe with an inner diameter of 50 mm, with diesel oil and tap water as the medium. They introduced dimensionless criteria numbers to quantify the flow state, combined with the theory of droplet breakup and coalescence, and proposed a semi-theoretical formula to predict flow pattern boundaries. They successfully divided the transition boundaries of stratified flow, intermittent flow, and dispersed flow, establishing the first semi-theoretical model based on dimensionless criteria, which provides a theoretical basis for the optimization of pipeline design.

Chen Jie [7] et al. integrated operational data from 12 domestic crude oil pipelines (with pipe diameters ranging from 89 mm to 377 mm), covering a water cut of 5%-90% and a flow velocity of 0.3-4.5 m/s. By modifying flow pattern transition parameters, they established a three-stage transition criterion for stratified flow-intermittent flow-dispersed flow, with a prediction accuracy of 92%. They also found that the viscosity ratio is a key factor affecting the stability of stratified flow, and high-viscosity crude oil is more likely to maintain stratified flow.

Liu Wenhong[8] et al. conducted experiments on oil-water two-phase flow in horizontal pipelines to study frictional resistance characteristics and found that the experimental results were highly consistent with numerical simulation results; Bai Yunxiang[9] observed the pressure drop and flow velocity distribution laws under different flow patterns through experiments, providing basic data for the establishment of mathematical models. Through visual observation and parameter measurement, experimental research directly captures key characteristics such as flow pattern transitions and pressure drop changes, serving as an important basis for verifying theoretical models and numerical simulation results.

3.2. Numerical Simulation Research Methods

Numerical simulation can simulate two-phase flow behaviors under complex flow conditions, providing strong support for theoretical research. Burlutskiy E[10] et al. used CFD technology to study the dispersion characteristics of oil-water two-phase flow in vertical pipelines, confirming that numerical simulation can accurately predict flow pattern transitions and pressure drop changes; Gu Hanyang[11] et al. adopted numerical methods to study the characteristics of stratified turbulent flow of oil-water two-phase flow in horizontal pipelines, revealing the influence of flow velocity and water cut on the flow field structure.

Desamala B[12] et al. combined numerical simulation with experiments to predict the flow pattern, volume fraction distribution, pressure, and velocity distribution of oil-water two-phase flow in horizontal pipelines, and found that the results of the two methods were highly consistent, verifying the reliability of this approach.

Numerical simulation can reproduce flow processes under different parameter combinations by constructing flow governing equations and setting boundary conditions, making up for the shortcomings of experimental research such as high cost and limited working conditions. The combination of experiments and simulations forms a "research loop where experiments verify simulations and simulations expand experiments," effectively promoting the development of oil-water two-phase flow theory.

4. Influencing Factors and Mechanism of Phase Inversion Point

The phase inversion phenomenon in heavy oil-water mixed flow is a complex behavior under the coupling of multiple physical fields, referring to the transition process of emulsions from water-in-oil (W/O) type to oil-in-water (O/W) type or water-in-oil-in-water (W/O/W) bicontinuous phase type. Its main influencing factors include temperature, water cut, and flow velocity. Research by Ogleby K D et al. found that oil phase viscosity significantly affects flow pattern transition: when the viscosity exceeds 100 mPa·s, the critical water cut for stratified flow decreases from 70% to 55%, and for every 1 m/s increase in mixed flow velocity, the pressure drop increases by 25%. They were the first to incorporate oil phase viscosity into flow pattern criteria, establishing the "Ogleby-Diagram" flow pattern map and a stratified flow pressure drop formula ($\Delta P/L = 0.012\mu_O^{0.8} V^{1.8}$) with a prediction error of < 15%.

Li [13] et al. revealed the regulatory mechanism of the synergistic effect of water cut and flow velocity on the phase inversion threshold through a self-developed multiphase shear turbulence experimental device. They found that there is a critical fluctuation phenomenon during the phase inversion process, and the critical exponential divergence characteristics of torque pulsation signals are consistent with the Ising model. Additionally, there is an irreversible hysteresis phenomenon between forward and reverse phase transitions. The critical water cut for phase inversion is mostly distributed in the range of 65%-75% and changes nonlinearly with flow velocity. At the microscale, the dynamic heterogeneity of the dispersed phase structure enhances during phase inversion, and the correlation length in the critical region increases exponentially, which is mutually confirmed by three-dimensional numerical simulation results.

Significant changes occur in the hydraulic properties of oil-water mixtures before and after the phase inversion point: before phase inversion (W/O type), the apparent viscosity increases with the increase in water cut; after phase inversion (O/W type), the viscosity decreases significantly with the increase in water cut and tends to stabilize. This abrupt change in viscosity leads to sharp variations in pipeline friction, which easily causes local overpressure problems. In addition, the contact mode between the external phase of the emulsion and the inner wall of the pipeline changes before and after phase inversion, directly affecting the pipeline corrosion rate. Lü Yuling[14], Cheng Hao[15], He Limin[16] et al. considered the influence of interfacial energy of the system on pressure drop, modified the pipeline pressure drop formula, and proposed a phase inversion pressure drop model; Wang Anpeng[17] et al. found through experimental comparison that the viscosity predictions of the Brinkman-Roscoe model and Furuse model at the phase inversion point of oil-water dispersed flow are most consistent with experimental data, providing an effective method for predicting the phase inversion point.

5. Comparative Study of Viscosity Prediction Models

The Andrade model[18], based on the Arrhenius equation, considers the viscous flow of heavy oil as an activation process, with viscosity showing an exponential relationship with temperature ($\mu = A \cdot \exp(E/RT)$). It has a simple form and few parameters, enabling it to quickly reflect the influence of temperature on viscosity. However, it only considers temperature as a single factor, ignoring key parameters such as pressure and composition, resulting in a narrow application range. The Walters model improves the Andrade model by introducing constants a and b related to temperature and oil properties to account for the influence of pressure on viscosity, which improves prediction accuracy. However, constants a and b need to be determined through experimental fitting, and the model does not involve the influence of heavy oil composition.

The Brooks-Calabrese model[19] comprehensively considers the effects of temperature, pressure, and relative density, establishing a viscosity prediction formula through empirical constants A, B, C, and D. It has relatively high prediction accuracy and a wide application range but requires a large amount of experimental data to fit the constants, and different types of heavy oil may need re-parameterization, resulting in poor universality. The Lohrenz-Bray-Clark model[20] is based on the corresponding states principle, correlating heavy oil viscosity with reference fluid viscosity and describing the fluid state through reduced temperature, reduced pressure, and acentric factor. It has a strong theoretical basis but involves complex calculations and relies on fluid critical parameters and acentric factors, limiting its application to heavy oils lacking such data.

5.1. Machine Learning Models

The SVM (Support Vector Machine) model[21], based on statistical learning theory, realizes viscosity regression through the optimal hyperplane in high-dimensional space. It has strong generalization ability and performs well with small sample data. However, the selection of kernel functions and parameters depends on experience, and it has high requirements for data preprocessing. The Artificial Neural Network (ANN) model proposed by Amo Oey[22] et al., which takes Reynolds number, viscosity ratio, etc., as inputs, predicts the pressure drop of oil-water flow in horizontal pipes through a multilayer perceptron network, with a mean absolute error of only 6.36%, significantly outperforming traditional empirical formulas; Wahid[23] et al. compared Gaussian Process (GP), Random Forest (RF), and ANN models and found that the GP model has significant advantages in handling flow pattern transitions, with a Median Absolute Percentage Error (MdAPE) of only 6.75%, which is 63.4% lower than that of traditional models, providing a new approach for viscosity and pressure drop prediction under complex working conditions.

6. Research on Pressure Drop and Temperature Drop Characteristics

6.1. Pressure Drop Characteristics and Influencing Factors

The pressure drop of heavy oil-hot water two-phase flow is a core parameter in the design of gathering and transportation systems, comprehensively affected by water cut, flow velocity, temperature, and pipeline geometric characteristics. Pouraria H [24] et al. found through numerical simulation that the flow pattern of oil-water two-phase flow in subsea pipelines transitions from W/O to O/W with increasing water cut, leading to a significant increase in pressure drop, which is consistent with the experimental results of Kumara W.A.S. [25] in horizontal pipelines.

The influence of flow velocity on pressure drop is manifested as follows: as the flow velocity increases, the flow pattern transitions from laminar to turbulent flow, the interaction between oil and water strengthens, and the pressure drop rises sharply, which is verified by the studies of Torres C F[26] and Loh W L[27].

Temperature indirectly affects pressure drop by influencing heavy oil viscosity: as temperature increases, heavy oil viscosity decreases, and the pressure drop decreases accordingly. CFD simulations by Gupta R[28] et al. show that increasing temperature is more effective in reducing pressure drop under high water cut conditions. Regarding pipeline geometric characteristics, Zong Y B[29] found that changes in the inclination angle of large-diameter inclined pipelines affect flow pattern distribution, thereby altering pressure drop; Ladosz Agnieszka[30] pointed out in microchannel research that channel shape (e.g., square) has a significant impact on pressure drop, suggesting that shape factors should be considered in the design of microscale gathering and transportation systems.

6.2. Temperature Drop Characteristics and Influencing Factors

During transportation, the temperature of heavy oil-hot water two-phase flow changes due to heat loss and frictional heat generation, which in turn affects viscosity and fluidity. Studies have shown that as temperature decreases, the rheological index of heavy oil decreases, and the shear thinning property becomes more prominent. Moreover, the higher the water cut, the more significant the influence of temperature on the rheological index. This is because molecular Brownian motion slows down at low temperatures, facilitating the ordered arrangement of disordered curled molecules along the shear direction. The viscosity-temperature curve is approximately linear in semi-logarithmic coordinates, and the slope decreases with decreasing shear rate, indicating that apparent viscosity is a coupled function of temperature and shear rate.

Heat loss is the main cause of temperature drop. Haim H[31] et al. proposed a calculation method for heat loss in buried pipelines, pointing out that pipeline burial depth, soil thermal conductivity, and ambient temperature are key influencing factors. Xie Ying[32] et al. calculated the axial temperature drop of hot oil pipelines using the predictor-corrector method, considering fluid properties, flow velocity, and pipeline parameters, and the prediction results are in good agreement with experimental data; Zhang Linxia[33] et al. proposed a simplified calculation method to facilitate engineering design.

Yao Haiyuan and Gong Jing et al. found through experiments on Bohai heavy oil that when the water cut is <40%, the flow is W/O dispersed flow, and viscosity increases exponentially with increasing water cut; when the water cut is >60%, it transitions to O/W type, and viscosity decreases significantly, with the critical phase inversion point at 55%. They constructed a flow pattern transition map, proposed an annular-core flow boundary prediction model, and achieved a 30% improvement in transportation efficiency.

Zhang [34] et al. integrated the Simulated Annealing Algorithm (SOA) with a BP Neural Network to optimize initial weights and thresholds. Combined with 12 key parameters, they predicted the wax deposition rate of crude oil pipelines with an error rate of <5%, which is 67% higher than that of traditional models. By correcting the influence of wax deposition on the heat transfer coefficient in the temperature drop model, the temperature drop prediction error in Changqing Oilfield was reduced from ±5°C to ±2°C, supporting the dynamic adjustment of water mixing ratio, reducing energy consumption by 18%, and decreasing pigging frequency by 30%.

7. Conclusion and Prospects

This paper systematically reviews the research progress on the flow characteristics of heavy oil-hot water two-phase flow, drawing the following conclusions: (1) Oil-water two-phase flow patterns are complex and diverse. The transition boundaries between stratified flow, intermittent flow, and dispersed flow can be predicted by dimensionless criteria and semi-theoretical models, with the viscosity ratio being the key factor affecting the stability of stratified flow; (2) The phase inversion point is a mutation point of two-phase flow characteristics, synergistically regulated by temperature, water cut, and flow velocity, and microscopically related to the enhanced dynamic heterogeneity of the dispersed phase structure; (3) Classical empirical models and machine learning models each have their advantages and disadvantages, with intelligent models such as ANN and GP performing better under complex working conditions; (4) Pressure drop and temperature drop characteristics are affected by the coupled influence of multiple factors. The combination of experiments and simulations is an effective means to reveal their laws, and intelligent optimization models can significantly improve the efficiency of gathering and transportation systems.

Future research can focus on three aspects: First, deepen the research on multi-physical field coupling mechanisms and establish a full-parameter coupling model considering flow patterns, phase inversion points, viscosity, pressure drop, and temperature drop; Second, expand the application scenarios of machine learning models and combine real-time monitoring data to realize dynamic optimization of gathering and transportation systems; Third, develop more adaptable prediction models and gathering-transportation technologies for complex conditions such as deep-sea and extreme environments, providing more comprehensive theoretical support for the efficient development of heavy oil resources.

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