Prediction of Wax Deposition in Shale Oil Multiphase Pipelines

Xiaoming Luo [1, *], Da Cao [1], Shengde Di [1]

[1] Shandong Provincial Key Laboratory of Oil, Gas and New Energy Storage and Transportation Safety, China University of Petroleum (East China), Qingdao 266580, China

Abstract. To tackle flow safety challenges arising from paraffin deposition in low-temperature shale oil multiphase conveying systems, this study establishes a multi-physics coupled model for predicting wax layer growth. The proposed modeling framework integrates a steady-state two-fluid model with thermodynamic equilibrium equations and a kinetics mechanism describing paraffin deposition. This mechanism explicitly accounts for molecular diffusion effects, deposit layer porosity, and shear stripping phenomena. The resultant integrated model facilitates comprehensive prediction of flow regimes, temperature profiles, pressure gradients, and wax layer thickness distribution within multiphase pipelines. Validation against experimental measurements and OLGA simulation results confirms the model's accuracy. Furthermore, the influence of operating temperature and fluid flow rate on the required pigging cycles is investigated. This model provides a robust theoretical foundation for ensuring the safe operation of multiphase pipelines transporting waxy shale oils.

Keywords: Shale oil; Multiphase pipelines; Wax deposition; Flow assurance.

1. Introduction

As the production of conventional oil and gas resources declines and becomes increasingly challenging, onshore petroleum development has increasingly shifted its focus to unconventional reserves [1]. With substantial resource volumes, concentrated distribution, and advancing extraction technologies, shale oil has become a crucial component of the energy systems in nations like the United States, China, and Russia [2]. Compared to traditional crudes, shale oil exhibits distinctive traits including elevated wax content, higher congelation points, and more rapid production decline rates. Consequently, paraffin deposition issues within pipelines intensify under low-temperature conditions. This leads to elevated flow resistance and potential blockages, posing significant obstacles to the safe and efficient gathering and transportation of this resource. Thus, developing precise predictive models and computational methods to accurately forecast paraffin accumulation characteristics in multiphase pipelines handling waxy shale crudes is essential for ensuring pipeline operational safety.

Initial research primarily investigated paraffin deposition within crude oil systems. Through experimental and theoretical analyses, researchers identified fundamental mechanisms including molecular diffusion, shear stripping, deposit aging, and shear dispersion [3]. Leveraging these mechanisms (one or more), Burger, Hamouda, Majeed, and Singh formulated kinetic models for paraffin accumulation in single-phase flows. Subsequent refinements by Hernandez [4], Venkatesan [5], and Obaseki [6] incorporated factors such as diffusional effects and aging within the deposit layer, substantially enhancing deposition prediction accuracy.

Predicting paraffin layer formation becomes markedly more complex in gas-liquid flows due to diverse flow patterns and intricate heat transfer mechanisms. Rygg [7] proposed a kinetics framework for gas-liquid systems based on molecular diffusion and shear dispersion, utilizing the Hayduk-Minhas correlation for the molecular diffusion coefficient. Matzain [8] investigated paraffin deposition using multiphase loop experiments, accounting for the combined influence of deposit layer porosity and flow regime on deposition characteristics, and subsequently proposing a biphasic oil-gas kinetics model. Duan [9] advanced beyond conventional one-dimensional formulations by developing a three-dimensional model for stratified flow within a bipolar coordinate system. This model enables predicting the circumferential distribution of deposited wax and elucidates the formation mechanism of crescent-shaped deposition profiles. Rittirong [10] analyzed hydro-thermal coupling phenomena during slug flow deposition via loop experiments, establishing a corresponding predictive model. Chi [11] conducted deposition experiments in a two-inch internal diameter annular test system, acquiring data for oil-gas stratified flow under various flow rates, which served as the basis for developing a multiscale predictive model.

In summary, while significant progress has been made in elucidating paraffin deposition mechanisms and advancing single-phase predictive capability, a systematic computational methodology specifically for multiphase flow regimes remains lacking. This study addresses this gap by establishing a coupled pressure-temperature field computational model grounded in the steady-state two-fluid model and thermodynamic principles. Building upon this foundation, a multiphase paraffin deposition model applicable across various flow patterns is developed, integrating molecular diffusion and shear stripping mechanisms. This model provides a robust theoretical basis for ensuring the operational security of multiphase pipelines transporting waxy shale oil.

2. Model construction

The predictive framework proposed in this work comprises three integrated modules:

1) Hydrodynamics Module: Building on a steady-state two-fluid formulation, this component calculates key pipeline flow parameters such as flow pattern, liquid holdup, and pressure drop gradients. 2) Heat Transfer Module: Utilizing the energy conservation equation while incorporating frictional dissipation effects, this module characterizes axial and radial temperature profile distributions along the pipe. 3) Paraffin Deposition Kinetics Module: Integrating wax molecular diffusion mass transfer with the shear removal mechanism, this component quantifies the deposition rate under coupled thermo-hydrodynamic conditions.

2.1 Hydrodynamic and heat transfer modules

The hydrodynamic computation component utilizes a steady-state two-fluid framework [34] (see Figure 1 for a simplified schematic). This formulation explicitly accounts for fluid geometric properties, gas-liquid phase interactions (incorporating wall shear stress and interfacial shear stresses), and interphase slip phenomena (represented by slip velocity). By solving the conservation equations for mass and momentum, this computational unit determines flow patterns, liquid volume fraction, pressure gradient distributions, and other key flow parameters.

To determine axial temperature profiles along the conduit, separate thermal energy transfer formulations are established for the gaseous phase, the liquid phase, and the gas-liquid mixture. The vapor-phase thermal equilibrium formulation combines external heat loss with heat generation from friction. Conversely, the liquid-phase thermal analysis primarily addresses heat dissipation to the surroundings.

2.2 Wax deposition modules

2.2.1 Molecular Diffusion Mechanism

Driven by the radial concentration gradient, paraffin molecules migrate from the bulk flow toward the pipe surface, progressively accumulating into a deposited layer. The deposition rate governing this transport mechanism follows Fick's first law of molecular diffusion:

$$\frac{\mathrm{d}m_{\mathrm{wax}}}{\mathrm{d}t}=\rho_{\mathrm{wax}}D_{\mathrm{ow}}A\frac{\mathrm{d}C_{\mathrm{wax}}}{\mathrm{d}r}=\rho_{\mathrm{wax}}D_{\mathrm{ow}}A\frac{\mathrm{d}C_{\mathrm{wax}}}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}r} \tag{1}$$

The temperature-dependent solubility behavior of paraffin crystals was determined via differential scanning calorimetry (DSC). Through interpolation algorithms, this parameter's variation across thermal regimes can be quantitatively mapped. Molecular diffusion coefficients are computed using the Wilke-Chang correlation (Equation 2).

$$D_{\mathrm{ow}}=7.4\times10^{-12}\frac{\left(xM_{oil}\right)^{1/2}T}{\mu_{oil}{V_{wax}}^{0.6}} \tag{2}$$

2.2.2 Shear stripping Effect and Porosity Influence

Within multiphase conveying systems transporting oil and gas, Matzain incorporated deposit porosity and shear removal effects, leading to the derivation of Equation 3, which quantifies deposited paraffin layer thickness in such systems.

$$\frac{\mathrm{d}\delta}{\mathrm{d}t}=\frac{\Pi_1}{1+\Pi_2}D_{\mathrm{ow}}\frac{\mathrm{d}C_{\mathrm{wax}}}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}r} \tag{3}$$

The porous architecture of deposited material entraps congealed hydrocarbon, enhancing wall deposit formation. Coefficient Π_1 quantifies this porosity effect, calculated via Equation 4.

$$\Pi_1=\frac{\mathrm{C}_1}{1-C_{\mathrm{L}}/100} \tag{4}$$

where C_1 = 15.0. CL denotes the oil concentration within the deposited paraffin layer, computed through Equation 5. The dimensionless Reynolds number N_{Re} incorporates the pipe's effective diameter and is determined by Equation 6.

$$\mathrm{C_L}=100(1-\frac{{N_{\mathrm{Re}}}^{0.15}}{8}) \tag{5}$$

$$N_{\mathrm{Re}}=\frac{\rho_1\left(\frac{U_{\mathrm{sl}}}{E}\right)d_{\mathrm{in}}}{\mu_1} \tag{6}$$

Coefficient Π_2 quantifies the shear stripping effect's suppression of deposit accumulation, stemming from hydrodynamic actions. Its value derives from Equation 7.

$$\Pi_2=\mathrm{C}_2{N_{\mathrm{SR}}}^{\mathrm{C}_3} \tag{7}$$

Shear removal intensity correlates with specific flow patterns, requiring distinct Reynolds number formulations for each hydrodynamic regime.

$$N_{\mathrm{SR}}=\begin{cases}\dfrac{\rho_{\mathrm{oil}}U_L\delta}{\mu_{\mathrm{L}}}, & \text{for stratified flow}\\ \dfrac{\rho_{\mathrm{mix}}U_L\delta}{\mu_L}, & \text{for bubble or slug flow}\\ \dfrac{\sqrt{\rho_{\mathrm{mix}}\rho_{\mathrm{oil}}}U_L\delta}{\mu_L}, & \text{for annular flow}\end{cases} \tag{8}$$

2.2.3 The effect of Water Content

Introducing aqueous phases into multiphase transportation systems modifies liquid phase properties, thereby impacting flow characteristics and thermal distribution profiles. These alterations drive variations in radial thermal gradients, ultimately influencing paraffin accumulation processes. Consequently, composite liquid properties are determined via weighted averaging.

Elevated aqueous fractions disrupt hydrocarbon phase continuity, impeding radial transport phenomena of paraffinic components and reducing accumulation rates. Following Zheng's experimental insights, the molecular diffusion coefficient is adjusted using Equation 9.

$$D_{\mathrm{ow}}'=D_{\mathrm{ow}}\frac{2}{2+\varphi^2} \tag{9}$$

2.3 Numerical method

This research establishes a steady-state biphasic formulation to resolve the multiphysics coupling among hydrodynamic, thermodynamic, and paraffin deposition phenomena in multiphase transport systems. The computational architecture synergistically integrates three modules—flow dynamics, thermal transfer, and precipitation kinetics—to holistically quantify operational parameters (velocity/liquid holdup/pressure gradient), thermal field evolution, and paraffin layer growth dynamics.

Implementing spatiotemporal discretization along the conduit, a bidirectional implicit iteration scheme operates through: (i) Forward thermal resolution using terminal pressure constraints via the heat transfer module; (ii) Backward hydrodynamic resolution with inlet thermal boundary conditions. Iterative reconciliation achieves coupled thermo-hydrodynamic equilibrium.

Subsequently, paraffin accumulation rates within microsegments are computed employing key determinants (e.g., molecular diffusivity, crystallization solubility), dynamically updating conduit geometry and heat transfer characteristics. Iterative gradient recalculation and cumulative thickness integration yield longitudinal-temporal evolution profiles of deposited layers.

3. Experimental Loop Benchmarking of Computational Framework

The multiphase paraffin accumulation experimental apparatus comprises an oil-water emulsion tank, air compression unit, mono-screw pump, thermostated immersion circulators, test loop assemblies, precision metrology instruments, and a digital monitoring platform (Figure 1). The modular pipeline assembly features a concentric stainless-steel structure: the inner conduit transports experimental fluid while the annular space circulates thermal transfer medium. This assembly utilizes a DN25.4 (NPS1) stainless-steel conduit incorporating a 3.0-meter removable segment designated as the deposit assessment zone. This test section operates within a thermoregulated enclosure simulating targeted cryogenic conditions.

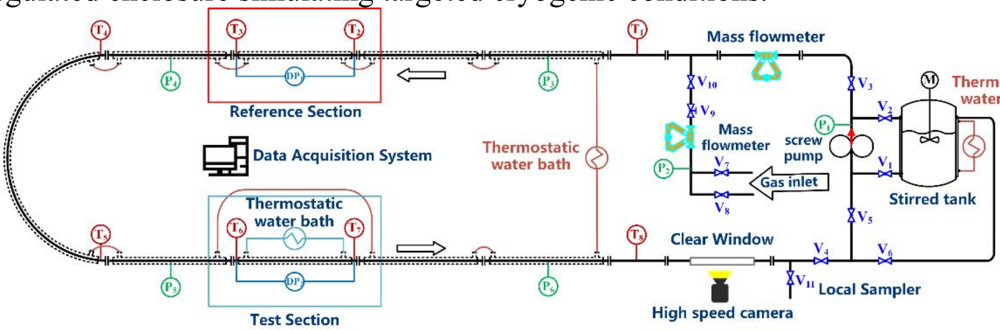

Figure 1. Schematic of paraffin deposition experiment loop system

The hydrocarbon test specimen originates from Changqing Oilfield shale production, with compressed air serving as the gaseous phase. Key properties of this shale-derived oil include: 39.5° API specific gravity, 29℃ wax appearance temperature (WAT), and 7.66% wax mass fraction.

Experimental investigations quantified gas-liquid velocity and flow topology effects on deposited paraffin thickness in shale oil systems. Model predictions were benchmarked against empirical results, with corresponding hydrodynamic parameters for each flow regime detailed in Table 1.

Table 1. Flow parameters of wax deposition experiment

Case	Flow regime	Usg [m/s]	Usl [m/s]
1	Slug flow	6	0.2/ 0.4/ 0.6
2	Slug flow	4/ 6/ 8	0.4
3	Stratified flow	4/ 6/ 8	0.1
4	Annular flow	18/ 19/ 20	0.15

Figure 2 juxtaposes computational outputs against empirical measurements across flow topologies. Discrepancy analysis between simulated and experimental paraffin accumulation thickness (Figure 3) demonstrates generally high predictive fidelity. Maximum thickness prediction discrepancies under slug, stratified, and annular flow conditions reach 17.07%, 19.53%, and 18.13% respectively. Heightened removal effects from elevated gas superficial velocities yield markedly reduced deposition in annular regimes compared to stratified/slug systems.

Systematic overestimation tendencies likely stem from omitting aging kinetics in wall-accumulated layers. During actual deposition processes, entrapped paraffin molecules undergo reverse diffusion into bulk flow over time – causing empirical thickness values to fall below simulated projections.

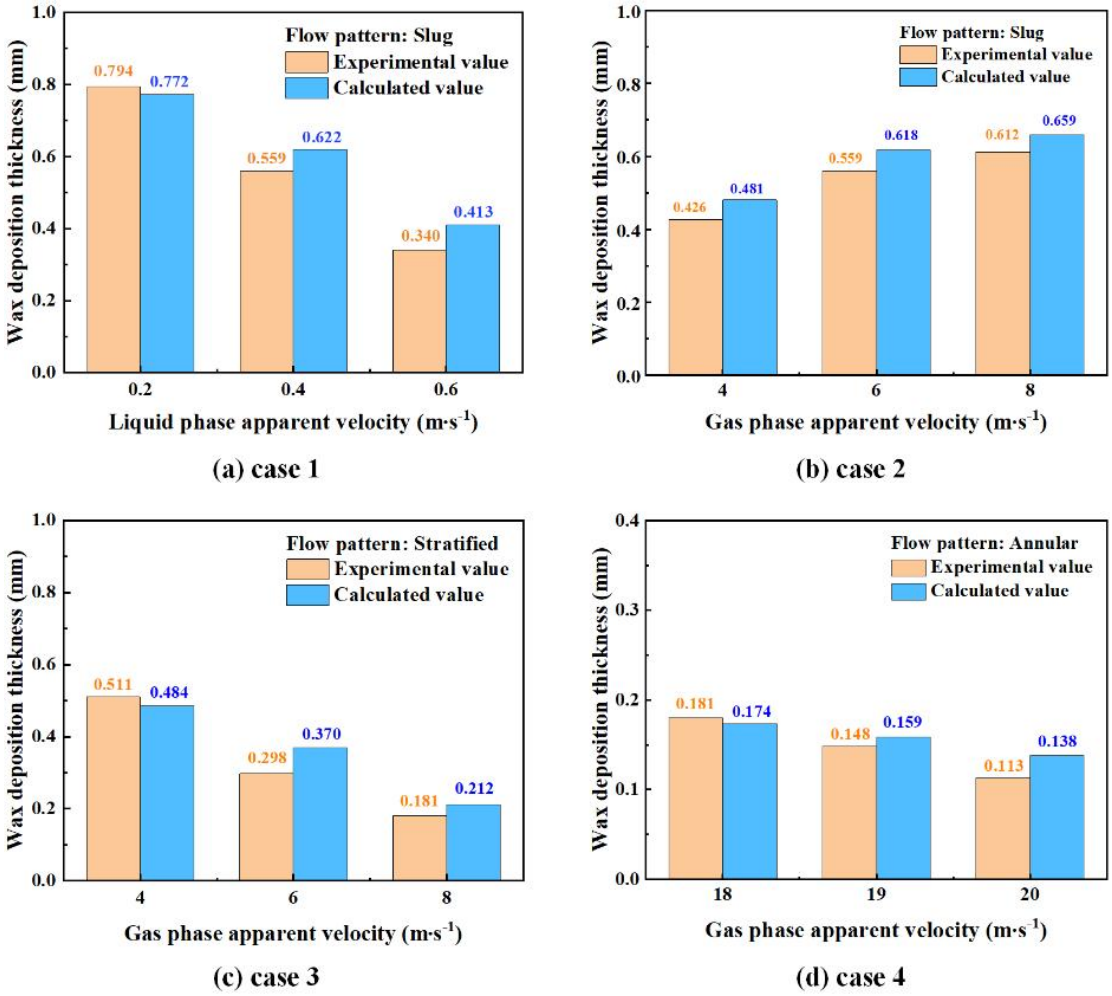

Figure 2. Comparison of model and experimental results

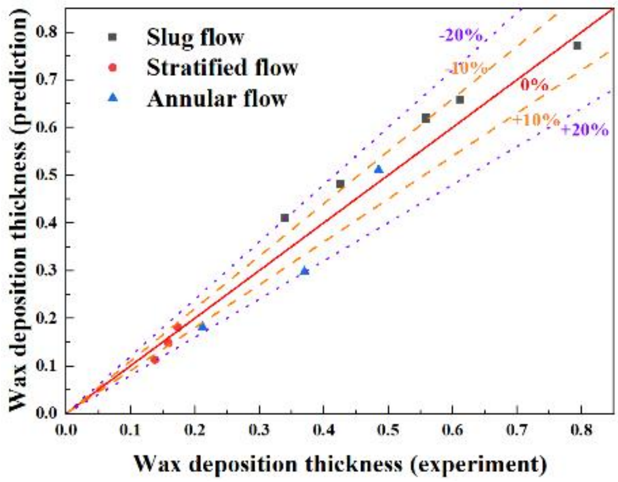

Figure 3. Error analysis of calculation results of wax deposition model

4. Summary

Addressing flow assurance challenges stemming from low-temperature paraffin accumulation in shale oil multiphase conveying systems, this research pioneers a multiphysics-coupled prediction framework for deposition layer growth. The methodology leverages a steady-state biphasic formulation to resolve hydrodynamic parameters (flow patterns, liquid holdup, pressure gradients), integrates coupled thermo-hydrodynamic fields, and incorporates mechanistic effects including molecular diffusion, deposit porosity, and shear removal dynamics. This establishes a validated kinetics model for multiphase deposition systems.

By synergizing convective heat transfer behavior with paraffin precipitation mechanisms, the framework enables holistic prediction of flow topology, pressure decay, thermal dissipation, and deposited layer thickness in multiphase transport infrastructures.

Model verification through experimental multiphase deposition testing demonstrates high prediction fidelity. Maximum deposition thickness deviations of 17.07% (slug flow), 19.53% (stratified), and 18.13% (annular) evidence robust performance. Results confirm the method's efficacy in guiding operational safety decisions for shale oil multiphase networks.

References

[1] Chen, Y., Jing, JQ., Karimov, R., Sun, J., Wang, K., Yang, F., Guo, YY., 2024. Experimental investigation on flow patterns and pressure gradients of shale oil–water flow in a horizontal pipe. International Journal of Multiphase Flow, 176.

[2] Zhao, XZ., Zhou, LH., Pu, XG., Jin, FM., Shi, ZN., Han, WZ., Jiang, WY., Han, GM., Zhang, W., Wang, H Ma, JY., 2020. Formation conditions and enrichment model of retained petroleum in lacustrine shale: A case study of the Paleogene in Huanghua depression, Bohai Bay Basin, China. Petroleum Exploration and Development, 47(5), 916–930.

[3] Li, BF., Guo, ZY., Zheng, LM., Shi, ER., Qi, B., 2024. A comprehensive review of wax deposition in crude oil systems: Mechanisms, influencing factors, prediction and inhibition techniques.

[4] Hernandez, O. C., Hensley, H., Sarica, C., Brill, J. P., Volk, M., Delle-Case, E., 2004. Improvements in single-phase paraffin deposition modeling. SPE Production & Facilities, 19(4), 237–244.

[5] Venkatesan, R, Fogler, HS., 2004. Comments on analogies for correlated heat and mass transfer in turbulent flow. AIChE Journal, 50(7), 1623-1626.

[6] Obaseki, M., Elijah, P.T., 2021. Dynamic modeling and prediction of wax deposition thickness in crude oil pipelines. Journal of King Saud University - Engineering Sciences, 30(6),437-445.

[7] Rygg, O B, Rydahl, A K, Ronningsen, H P., 1998. Wax deposition in offshore pipeline systems. United Kingdom: N. p., 1998. Web.

[8] Apte, M.S., Matzain, A., Zhang, H.Q., Volk, M., Brill, J.P., Creek, J.L., 2001. Investigation of paraffin deposition during multiphase flow in pipelines and wellbores—Part 2: Modeling. Journal of Energy Resources Technology, 123(2), 150–15

[9] Duan, J., Liu, H., Guan, J., Hua, W., Jiao, G., Gong, J., 2016. Wax deposition modeling of oil/gas stratified smooth pipe flow. AIChE Journal, 62(7), 2550–2562.

[10] Rittirong, A., Panacharoensawad, E., Sarica, C., 2017. Experimental study of paraffin deposition under two-phase gas/oil slug flow in horizontal pipes. SPE Production & Operations, 32(1), 99–117.

[11] Chi, YD, Sarica, C., Daraboina, N., 2019. Experimental investigation of two-phase gas-oil stratified flow wax deposition in pipeline. Fuel, 247(1), 113-125.