Petroleum and Coal

Article **Open Access**

Characterization of Flow-rate dominated Deposition on Flow Assurance Investigations associated with Multi-Phase Hydrocarbon Flow through Pipe Lines

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Received November 15, 2024; Accepted March 10, 2025

Abstract

Flow assurance, having a critical impact on both capital expenditure as well as operational expenditure, the role of flow assurance professionals remains to be very critical and sensitive in the planning and engineering of the varieties of hydrocarbon field development projects. Fundamentally, the precipitation of solids and the subsequent deposition of solids are not only two different phenomena, but also requires sound knowledge on two different disciplines including chemical engineering and civil engineering. In essence, precipitation aspect of flow assurance of solids have been given the required attention, while, the flow-rate dominated deposition aspect is not being given the required attention. This is because, the precipitation aspect remains associated with chemical reactions related with chemistry/chemical-engineering, while the flow-rate dominated aspect remains associated with civil engineering application (sedimentation phenomenon). It is to be clearly noted that the traditional transport phenomenon associated with chemical engineering, in general, do not include the aspects of sedimentation like the details included in civil engineering. In addition, investigation on the deposition of solids remains to be more complex than the investigation leading to the precipitation of solids. It is further to be noted that at the laboratory-scale, we acquire the required data on precipitation, while, we generally, do not take into account the required details on deposition aspect as the reduction in temperature along the pipeline and across the wall of a pipeline at the laboratory-scale do not replicate a typical real field scenario. Given this background, the primary objective of the present article is to provide a simple set of already existing mathematical model for characterizing the flow-rate dominated deposition aspect of flow assurance. It is expected that this article would be able to bridge the gap between chemistry dominated precipitation and flow-rate dominated deposition of flow assurance solids.

Keywords: *Flow assurance; Asphaltene; Paraffin wax; Gas hydrate; Precipitation and deposition.*

1. Introduction

The transport of oil and gas through pipelines (running over 2-20 km) from subsurface (underground, 2-4 km deep) petroleum reservoirs up to the surface-based processing facilities remains to be the basis of flow assurance investigations; and thereby, flow assurance studies ensure low-risk and cost-effective delivery of multi-phase fluid flow through saturated pipelines [1-2]. The fluid velocity in liquid-carrying pipelines hangs around 2-4 m/s, while, the gas velocity in pipelines carrying gas-dominated flow hangs around 50-60 m/s. Flow assurance studies remain different from fluid dynamics in the sense that flow assurance studies integrate the phase behavior of the transported oil/gas along with the chemistry of precipitating solids associated with the transported oil/gas flow (formation brines with varying salinities along with light/heavy oil and/or water-vapor-saturated-gas/gas-condensates). In the context of blocking of flow passage by the chemical solids, it was initially identified that the precipitation and the subsequent deposition of paraffin wax (the vertical solubility line of paraffin wax crosses the bubble point line, which remains to be a strong function of temperature; and mostly, paraffin wax gets deposited in the temperature range between 30 and 40 degrees C) remained to be the most general cause for the blockage of the flow through the transported pipelines. With time, scientists also recognized that role of natural gas hydrates (gas hydrates forms upon crossing the bubble point line, where, the temperature of the transported fluids gets reduced and significantly cooled; and mostly, gas hydrates form under typical conditions of 10 MPa and 20 degrees C during its transport through pipelines) and asphaltenes (asphaltenes generally form at high pressure and high temperature, near the critical point of the hydrocarbon phase envelope; and the subsequent precipitation of asphaltenes commences marginally above the bubble point line and this precipitation gets continued during the crossing of bubble point line, and gets over, slightly below the bubble point line as the light gases present in the oil gets liberated and thereby increasing the density of the oil, which essentially breaks the precipitation of asphaltenes) in effectively blocking the flow passage of oil/gas pipelines. Recently, the formation, precipitation and deposition of naphthenates have been found out in blocking oil/gas transporting pipelines that require flow assurance measures [3-4]. Apart from these four organic deposits (paraffin wax, natural gas hydrate, asphaltene and naphthenates), an inorganic solid also is found to block oil/gas pipelines in the form of scale formation. Since, flow assurance has a profound impact on both capital expenditure as well as operational expenditure, the role of flow assurance professionals remains to be very critical and sensitive in the planning and engineering of the varieties of hydrocarbon field development projects.

2. Multi-phase hydrocarbon flow

The chemistry dominated flow assurance of solids remains manifested by chemical thermodynamics, which essentially involves intensive properties including pressure, temperature, concentration and chemical potential. However, the flow-rate dominated deposition process remains dominated by transport phenomenon, which essentially involves mass transfer, momentum transfer and heat transfer. Thus, fundamentally, the precipitation of solids and the subsequent deposition of solids are not only two different phenomena, but also requires sound knowledge on two different disciplines including chemical engineering and civil engineering.

With reference to the chemistry dominated precipitation of flow assurance solids from multiphase liquid solutions, the focus primarily remains dominated by different aspects of solubility and chemical thermodynamics in the absence of explicitly considering the reaction kinetics; and the entire focus on chemical thermodynamics rests on initial and final states. Although, chemical thermodynamics does not depend on an explicit pathway, the precipitation theories still remain to be different for various flow assurance solids. For example, (a) conventional solution theory has met with an accomplishment towards characterizing asphaltene precipitation; and asphaltene precipitation essentially involves the expelling out of solid asphaltene particles from liquid solution and it becomes suspended in the liquid flow upon the flow becoming unstable; and this instability results from the variations in pressure, temperature, composition of the production fluid and the viscosity of oil; and among the variables pressure and temperature, pressure (in particular, asphaltene onset pressure) is considered to be the critical factor in dictating the precipitation of asphaltenes because the aliphatic components in the oil increases leading to the precipitation of asphaltenes upon reduction in pressure (although, asphaltene onset pressure gets reduced upon increasing the temperature); (b) the complex interplay between chemical potential and fugacity has met with an accomplishment towards characterizing paraffin wax precipitation [5-8]; and such precipitation occurs in pipelines and subsequently constrict the flow over time, when the temperature of the transported fluid is at or below the Wax Appearance Temperature (WAT); (c) thermodynamic modelling of dissociation/equilibrium lines has met with an accomplishment towards characterizing natural gas hydrate precipitation; and such hydrate formation forms under the combination of low temperature and high pressure, where the temperature of gas in the pipeline declines below the saturation temperature, when water vapor commences to condensate leading to the formation of hydrate nucleation; which grows over time, constricting the smooth fluid flow [9]; (d) the traditional use of solubility product constants has met with an accomplishment towards characterizing inorganic scaling [10]; and (e) application of carboxylic acid chemistry has met with an accomplishment towards characterizing naphthenate precipitation. Thus, precipitation aspect of flow assurance of solids have been given the required attention, while, the flow-rate dominated deposition aspect is not being given the required attention. This is because, the precipitation aspect remains associated with chemical reactions related with chemistry/chemical-engineering, while the flow-rate dominated aspect remains associated with civil engineering application (sedimentation phenomenon). It is to be clearly noted that the traditional transport phenomenon associated with chemical engineering, in general, do not include the aspects of sedimentation like the details included in civil engineering. In addition, investigation on the deposition of solids remains to be more complex than the investigation leading to the precipitation of solids. It is further to be noted that at the laboratory-scale, we acquire the required data on precipitation, while, we generally, do not take into account the required details on deposition aspect as the reduction in temperature along the pipeline and across the wall of a pipeline at the laboratory-scale do not replicate a typical real field scenario. In essence, the drop in temperature directly leads to the formation of natural gas hydrates as well as leads to the precipitation of paraffin wax, while, indirectly, leads to the precipitation of inorganic solids, and less directly leads to the formation of asphaltenes and nahthenates.

3. Mathematical model

The pipeline is conceptualized to be a long heat exchanger tube; and the fluid in the pipeline gets cooled from the outside lower temperature. If the ambient temperature is assumed to be constant, then, for a steady-state pipeline flow, the bulk temperature can be estimated using eqn. (1).

$$T_2 = T_0 + (T_1 - T_0)\ exp\left[\frac{-U\pi d}{mC_p} L\right] \qquad (1)$$

In eqn. (1), T_2 represents the temperature at a downstream location (pipeline outlet fluid temperature); T_1 represents the upstream inlet temperature (pipeline inlet fluid temperature); L represents the length of the pipeline segment (in m) considered for a given outside temperature; U represents the overall heat transfer coefficient, which varies between 10 and 100 W/m^2 . K for pipelines without insulation, and it varies between 1 – 5 W/m^2 . K for the insulated subsea pipelines; *m* represents the mass flow rate within the pipeline (kg/s), and there will be various fluid phases present in the pipeline and each fluid phase will have its own mass fraction; T_o represents the constant outside temperature (K); *d* represents the internal diameter of the pipeline (m); and C_p represents the heat capacity of the flowing fluid (J/kg . K).

The cooling of the flowing fluid within the pipeline remains to be directly related with the product of mass flow rate within the pipeline and the heat capacity of the flowing fluid (mC_p); and it also remains directly related with the changes in temperature between pipeline's upstream and downstream fluid temperature (T_1-T_2). The bulk temperature in eqn. (1) approaches asymptotically the outside temperature with time. The time taken by the pipeline to cool down to a temperature, where the flow assurance solids starts precipitating can be estimated from shut-down temperature, which essentially represents the time-frame available before a flowline must be started-up again towards avowing the precipitation of solids.

In addition to temperature drop, pressure drop also remains to be critical towards the precipitation and deposition of flow assurance solids. The total pressure drop in the pipelines resulting from the summation of gravitation, acceleration and friction is given in eqn. (2) and this equation is based on the momentum equation for steady-state, one-dimensional fluid flow under isothermal conditions. The change in length associated with gravitation and friction terms represent the actual length of the pipeline, while, the change in velocity associated with gravitation term represents the velocity change from one cross-section to another.

$$\Delta p_{total} = \Delta p_{gravitation} + \Delta p_{acceleration} + \Delta = \rho g\ sin\alpha\ \Delta L + \rho u\ \Delta u + \frac{f}{2}\frac{1}{d}\ \rho u^2\ \Delta L \qquad (2)$$

The pressure drop in liquid pipelines as measured in eqn. (3) can be used towards estimating the thickness of deposits in pipelines (albeit their uneven distribution).

$$\Delta p_{wall\ friction} = 8f\ \frac{L}{d}\rho\left(\frac{q}{\pi d^2}\right)^2 = \frac{fL\rho}{2\pi^2}\ \frac{q^2}{d^5} \qquad (3)$$

The pressure drop in natural gas pipelines can be estimated as a function of inlet pressure (p_1); outlet pressure (p_2); cross sectional area of flow (A); molecular weight of natural gas (M kg/kmol); mass flow rate (m kg/s); compressibility factor (z); mean value of the temperature in the considered pipeline segment (T K); and it is expressed in eqn. (4).

$$\frac{dA^2M}{fm^2zRT}(p_2^2 - p_1^2) - \frac{d}{f}ln\left(\frac{p_2^2}{p_1^2}\right) + L = 0 \quad (4)$$

The frictional and hydrostatic pressure drop in non-horizontal natural gas pipelines is given in eqn. (5) by considering the effect of acceleration to remain to be insignificant.

$$p_2^2 = p_1^2 \ exp\left(-2\frac{M}{zRT}g \ sin\alpha L\right) - \frac{\left(\frac{fm^2}{2A^2d}\right)}{g \ sin\alpha\left(\frac{M}{zRT}\right)^2}\left[1 - \exp\left(\frac{2gM}{zRT} \ sin\alpha L\right)\right] \quad (5)$$

Fourier's law dictates the heat transfer from a pipe wall to the interior of the pipe, while Newton's law of cooling dictates the steady-state heat flow equation, which involves the estimation of overall heat transfer coefficient (resistance). The total heat transfer coefficient (U_i) for a circular pipe is given in eqn. (6) expressed as a function of interior (h_i) and exterior (h_e) heat transfer areas; and also, as a function of interior (R_{fi}) and exterior (R_{fe}) fouling resistances.

$$\frac{1}{U_i} = \frac{1}{h_i} + R_{fi} + \frac{r_i}{k}\ln\left(\frac{r_e}{r_i}\right) + \left(\frac{1}{h_e} + R_{fe}\right)\frac{r_i}{r_e} \quad (6)$$

The fundamental law for the transfer of thermal energy (given by Fourier's law) in terms of energy in the form of heat (q W) as a function of temperature gradient (dT/dx K/m), the cross sectional area (A m^2) and thermal conductivity (λ W/m . K) is given in eqn. (7).

$$q = -\lambda A \frac{dT}{dx} \quad (7)$$

The fundamental law ensuring mass conservation is expressed by Fick's law and it is given in eqn. (8), which describes molar flux (J mol/s . m^2) as a function of concentration gradient (dc/dx mol/m^3) and molecular diffusivity constant (D m^2/s).

$$J = -D\frac{dc}{dx} \quad (8)$$

The fundamental law ensuring momentum conservation for liquid flow is expressed by Newton's law of viscosity and it is given in eqn. (9a), which describes wall shear stress (τ N/m^2) as a function of velocity gradient (du/dx s^{-1}) and fluid viscosity (μ Pa.s).

$$\tau = \mu\frac{du}{dx} \quad (9a)$$

The fundamental law ensuring momentum conservation for gas flow is given in eqn. (9b) under steady-state conditions of isothermal flow. Since, gas remains to be compressible, the pressure drop due to acceleration {d(ρu^2)/dx} is expressed as a function of total pressure drop (dp/dx); the pressure drop due to wall friction ($f\rho u^2/2d$); and the pressure drop due to hydrostatic head (ρg sinα).

$$\frac{d(\rho u^2)}{dx} = -\frac{dp}{dx} - \frac{f\rho u^2}{2d} - \rho g \ sin\alpha \quad (9b)$$

The fundamental law for describing fluid flow is given in eqn. (10) and it is expressed by Darcy's law, where, the volumetric fluid flow rate (q m/s) is expressed as a function of pressure gradient (dp/dx Pa/m); intrinsic permeability (k m^2) and fluid viscosity (μ Pa.s).

$$q = -\frac{k}{\mu}\frac{dp}{dx} \quad (10)$$

The fundamental law for deducing the mean fluid velocity is given in eqn. (11) and it is expressed by Poiseulli's law, which describes the mean fluid velocity (u m/s) as a function of pressure gradient along the flow direction (dp/dx Pa/m); fluid viscosity (μ Pa.s) and the distance from the centerline to the solid wall (R m).

$$u = \frac{1}{8\mu}(R^2 - r^2)\frac{dp}{dx} \quad (11)$$

In the case of turbulent flow, the wall shear stress as given in eqn. (12) can be expressed as a function of eddy diffusivity ($\dot{\varepsilon}$ m^2/s) and eddy viscosity {η(=$\rho\dot{\varepsilon}$) Pa.s}.

$$\tau = (\mu + \eta)\frac{du}{dx} \quad (12)$$

Assuming the solid particles to be at rest initially, the particle velocity (u_p m/s) as a function of time (t s) can be expressed in terms of terminal settling velocity (u_{TS}) and particle relaxation time (τ) as given in eqn. (13).

$$u_p(t) = u_{TS\left\{1-\exp\left(\frac{-t}{\tau}\right)\right\}} \quad (13)$$

In eqn. (13), the particle relaxation time is expressed as a function of particle density (ρ_p kg/m^3); particle diameter (d_p m) and fluid viscosity (μ Pa.s) as given in eqn. (14).

$$\tau = \frac{\rho_p\, d_p^2}{18\, \mu_f} \tag{14}$$

The increase in the thickness of deposited solids as a function of time is given in eqn. (15) and (16), where k_1 and k_2 represent the constant coefficients.

$$\frac{dx}{dt} = k_1 - k_2 x \tag{15}$$

$$x = \frac{k_1}{k_2}\left[1 - \exp(k_2 t)\right] \tag{16}$$

The above set of equations provide a relatively simple mathematical model to take into consideration of flow-rate dominated deposition aspect of flow assurance solids, while, Gudmundsson [11] cab be referred for further details, which is beyond the scope of the present study.

4. Conclusions

The present article has made an attempt in order to provide a simple set of already existing mathematical model for characterizing the flow-rate dominated deposition aspect of flow assurance. It is expected that this article would be able to bridge the gap between the characterization of chemistry dominated precipitation and flow-rate dominated deposition of flow assurance solids. The set of equations comprising the mathematical modeling includes (a) the estimation of mass, momentum and energy conservation; (b) the particle velocity of solids during its precipitation; and (c) the thickness of the deposited solids along the pipelines.

Acknowledgement: *There is no funding associated with this work.*

Conflict of interest: *The author declares no competing interest.*

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