Journal of Petroleum Science and Engineering 129 (2015) 77–87

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Study of asphaltene deposition in wellbores during turbulent flow

D.M. Paes [a], P.R. Ribeiro [a,*], M. Shirdel [b], K. Sepehrnoori [b]

[a] State University of Campinas, Campinas, SP, Brazil
[b] The University of Texas at Austin, Austin, TX, USA

ARTICLE INFO

Article history:
Received 30 October 2014
Accepted 3 February 2015
Available online 24 February 2015

Keywords:
Asphaltene
Flow assurance
Production
Petroleum

ABSTRACT

During petroleum production, asphaltene particles can precipitate from the crude oil due to pressure, temperature, and composition changes along the fluid path from the reservoir to the surface. Once precipitated, those particles can deposit in the inner surface of production tubings, restricting the available flow area and reducing flow rates. To enable a better understanding of that complex mass transfer problem, a new methodology was proposed in this paper. The methodology involved a comprehensive review of fundamental concepts of the mass transfer and particle deposition theories, placing the asphaltene deposition within a more general context of particle deposition during turbulent flow. Six published particle deposition models (Lin et al., 1953. Ind. Eng. Chem. 45 (3), 636–640. ⟨http://dx.doi.org/10.1021/ie50519a048⟩; Friedlander and Johnstone, 1957. Ind. Eng. Chem. 49 (7), 1151–1956. ⟨http://dx.doi.org/10.1021/ie50571a039⟩; Beal, 1970. Nucl. Sci. Eng. 40, 1–11; El-Shobokshy and Ismail, 1980. Atmos. Environ. 14 (3), 297–304. ⟨http://dx.doi.org/10.1016/0004-6981(80)90063-3⟩; Papavergos and Hedley, 1984. Chem. Eng. Res. Des. 62, 275–295.; Escobedo and Mansoori, 1995. Paper SPE 29488 presented at the SPE Production Operations Symposium, Oklahoma City, Oklahoma, 2–4 April. ⟨http://dx.doi.org/10.2118/29488-MS⟩) were studied and validated with four published aerosol experimental data sets (Friedlander, 1954. Deposition of Aerosol Particles from Turbulent Gases. Ph.D. Dissertation, University of Illinois, Urbana, Illinois (July 1954); Wells and Chamberlain, 1967. Br. J. Appl. Phys. 18, 1793–1799. ⟨http://dx.doi.org/10.1088/0508-3443/18/12/317⟩; Liu and Agarwal, 1974. J. Aerosol Sci. 5 (2), 145–155. ⟨http://dx.doi.org/10.1016/0021-8502(74)90046-9⟩; Agarwal, 1975. Aerosol Sampling and Transport. Ph.D. Dissertation. University of Minnesota, Minneapolis, Minnesota (June 1975)). Based on the results of the study, Beal's (1970. Nucl. Sci. Eng. 40, 1–11) model was selected as the most suitable to predict particle deposition and was considered adequate also to predict asphaltene deposition (limiting its application to similar ranges of Reynolds numbers, Schmidt numbers and dimensionless relaxation times in relation to those covered in the validation study). Finally, that model was applied in a sensitivity analysis to evaluate the most important parameters and transport mechanisms governing asphaltene deposition in wellbores.

1. Introduction

Asphaltenes are defined as the crude oil fraction that is soluble in aromatic solvents (*e.g.* toluene) but insoluble in light alkanes (*e.g.* *n*-pentane). Under reservoir conditions, they tend to remain dispersed in the oil as a colloidal suspension. During petroleum production, changes in oil temperature, pressure and composition can disturb the stability of the colloidal suspension and lead to asphaltene precipitation. That process can happen both in the reservoir (due to normal depletion or to the injection of incompatible fluids in EOR operations) and in the wellbore(due to changes in the thermodynamic conditions of produced fluids). The primary precipitates have sizes around several nanometers and,after agglomerating to each other, reach tens of micra (Eskin et al., 2009). The asphaltene particles' density is usually evaluated as 1200 kg/m^3.

Once precipitated, the solids can be deposited along the fluid path from the reservoir to the surface, leading to operational problems, safety hazards and an overall decrease in production rates. Kokal and Sayegh (1995) published an extensive literature survey on field experiences with asphaltene deposition in wellbores. In most cases the problems occurred in the early production stages of the wells after a short initial period of high flow rates (turbulent flow). The deposits were observed to be restricted to tubing depths where fluid pressure was above the oil bubble point, indicating that the multiphase flow with gas somehow hindered deposition. Historically, light oils, with low asphaltene content, have showed themselves to be more prone to develop problems with asphaltenes than heavy oils. That behavior can be explained by the fact that heavy oils, rich in asphaltene content, tend to be rich also in resin content, and the resins act as peptizing agents to stabilize the asphaltenes suspended in the oil (Leontaritis and Mansoori, 1988).

* Corresponding author.
E-mail address: ribeiro@dep.fem.unicamp.br (P.R. Ribeiro).

http://dx.doi.org/10.1016/j.petrol.2015.02.010
0920-4105/

Nomenclature

C	instantaneous particle concentration (at y) (g/cm^3)
C_{avg}	average particle concentration on flow (g/cm^3)
$\overline{C}$	time averaged mean particle concentration (at y) (g/cm^3)
C'	fluctuating particle concentration (at y) (g/cm^3)
D_B	Brownian diffusivity (cm^2/s)
d_t	tube diameter, cm [in.]
d_p	particle diameter, cm, [μm]
f_F	Fanning friction factor
K_B	Boltzmann constant, 1.38 × 10^{-16} g-cm^2/K-s^2
K_d	transport coefficient or particle deposition velocity (cm/s)
K_d^+	dimensionless particle deposition velocity
m_p	particle mass, g
N	radial particle flux (at y) (g/cm^2-s)
N_0	radial particle flux at an infinitesimal distance from tube wall (g/cm^2-s)
N_{Sc}	Schmidt number
N_{Re}	Reynolds number
s	particle stopping distance (cm)
t	time (s)
t_e	lifetime of the near-wall eddies (s)
t_p	particle relaxation time (s)
t_+	dimensionless relaxation time
T	fluid temperature, K [°C]
u	instantaneous axial fluid velocity (at y) (cm/s)
U	average flow velocity, cm/s [m/s]
$\overline{u}$	time averaged mean axial fluid velocity (at y) (cm/s)
u'	fluctuating axial fluid velocity (at y) (cm/s)
u'_{RMS}	RMS value of u' (cm/s)
u_*	friction velocity (cm/s)
V_0	radial particle velocity at the beginning of the free-flight (at $y=s$) (cm/s)
v	instantaneous radial fluid velocity (at y) (cm/s)
$\overline{v}$	time averaged mean radial fluid velocity (at y) (cm/s)
v'	fluctuating radial fluid velocity (at y) (cm/s)
v'_{RMS}	RMS value of v' (cm/s)
x	particle position during free-flight (cm)
y	distance from pipe wall (cm)
ε	eddy diffusivity (at y) (cm^2/s)
μ	dynamic viscosity, g/cm-s = poise [cP]
ν	kinematic viscosity (cm^2/s)
ρ	fluid density, g/cm^3 [kg/m^3]
ρ_p	particle density, g/cm^3, [kg/cm^3)
τ	shear stress at y (g/cm-s^2)

Escobedo and Mansoori (1995) published the first asphaltene deposition model found in literature. The model was developed for vertical turbulent streams and was based on previous models used to predict aerosol deposition (microscopic liquid or solid particles dispersed on air currents). The authors considered that the asphaltene particles were transported to pipe walls by a combination of diffusive and convective mechanisms. Because of the inexistence of published data for asphaltene deposition, they validated the model with aerosol experimental data, collected by Friedlander and Johnstone (1957).

A different approach was taken by Ramirez-Jaramillo et al. (2006), who modeled asphaltene deposition using concepts derived from the wax deposition theory. They attributed the radial transport of asphaltene particles exclusively to molecular diffusion, with a major dependence on the temperature profile inside the pipe. That approach was later criticized by other authors (Eskin et al., 2009) and did not have continuity in literature, since the field experience shows little influence of fluid temperature on asphaltene deposition.

Jamialahmadi et al. (2009) performed experiments to measure asphaltene deposition in a flow-loop apparatus. They verified that after an initial period of pure deposition, particle re-entrainment on flow started to occur due to the erosion of the deposits. Unfortunately, those two events (particle deposition and re-entrainment) could not be measured separatelyand the deposition rates published were the net result of them. To represent those deposition rates, the authors used equations developed for aerosol deposition (Cleaver and Yates, 1975), which accounted for diffusive and convective mechanisms. In addition to that, they used a correlation to account for particle re-entrainment on flow (Watkinson and Epstein, 1970). The results obtained agreed with the experimental measures, but some parameters in the re-entrainment correlation had to be adjusted for that.

Shirdel et al. (2012) studied the application of some particle deposition models (Friedlander and Johnstone, 1957; Beal, 1970; Cleaver and Yates, 1975; Escobedo and Mansoori, 1995) to predict published experimental data. In the first part of the paper, they used Friedlander and Johnstone's (1957) aerosol data set, which was exempt of particle re-entrainment. In the second part, they used Jamialahmadi's et al. (2009) asphaltene data set, which represents the net result of deposition and re-entrainment. Based on the studies performed, the authors concluded that both Beal's (1970) and Escobedo and Mansoori's (1995) models were adequate to predict asphaltene deposition.

1.1. Objectives

The main objective of the present work was to investigate the contribution of diffusive and convective mechanisms to promote the radial transport of asphaltene particles, complementing the first part of Shirdel's et al. (2012) study with a more detailed investigation of particle-fluid interaction and with more published models and experimental data sets. Exclusively smooth vertical tubings were considered, which nullified the influence of pipe roughness and gravitational forces on transport rates. Electrostatic effects were not addressed either, although they are important for asphaltene deposition and their investigation is recommended to complement the present study.

More specifically, the three objectives of this research were: (i) to theoretically investigate the radial transport of asphaltene particles, clarifying the main mechanisms that contribute for this complex problem, (ii) to select an accurate model from literature to predict asphaltene deposition rates, and, (iii) to perform a sensitivity analysis with the selected model to identify the most important parameters governing asphaltene deposition.

1.2. Methodology

The literature survey performed showed that the main line of research applied to model asphaltene deposition is that derived from the aerosol theory. That line considers convective and diffusive mechanisms acting to promote the radial transport of asphaltenes, with limited influence of fluid temperature in the process (contrary to what proposes the line derived from the wax deposition theory). It should be noticed, however, that there are substantial differences between asphaltene and aerosol deposition, especially because of the medium in which the particles are dispersed (liquid and gas, respectively). Those differences should be properly addressed before aerosol models and experimental data sets are applied in the study of asphaltene deposition. Such analysis has not been done by previous