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CFD modeling of high inertia asphaltene aggregates deposition in 3D turbulent oil production wells

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ABSTRACT

As a high pressure crude oil flows in production well, due to pressure drop, asphaltenes precipitate and eventually deposit on the tubing wall. In this work the flow of crude oil with high inertia asphaltene aggregates deposition phenomenon was simulated by Eulerian-Lagrangian method using 3D computational fluid dynamics (CFD) tool. The k-ω model was used to simulate the fully developed turbulent flow of crude oil in the well column. Due to the lack of experimental data for high inertia asphaltene aggregates deposition in turbulent pipe flow, the modeling results were validated with the available aerosol data. The results showed that the k-ω turbulent model can precisely predict the high inertia asphaltene particles deposition phenomenon. The effects of oil velocity, surface roughness and asphaltene concentration on deposition velocity were investigated. The modeling results indicated that asphaltene deposition velocity was independent of surface roughness and particles number in the crude oil. In contrast, the deposition velocity increased significantly with oil flow velocity. The results also showed that increasing of oil velocity leads to decrease asphaltene deposition flux. Finally, a slight change inwell cross-section area due to asphaltene deposition was observed.

1. Introduction

Petroleum is now an important factor in the development of nations, including in economy, politics and technology. This valuable natural material is generally composed of hydrocarbons in gas, liquid and solid states that is recovered from the underground reservoirs and transferred to the surface by pipelines. The liquid component in the petroleum is known as crude oil (Marinho et al., 2012). Crude oil is assumed to be a complex polydispersed mixture of hydrocarbons and other compounds (Mohammadi and Richon, 2007)that contains a variety of substances with different chemical structures and molecular weights (da Silva et al., 2013). The carbon content of crude oil normally is in the range of 83–87%, and the hydrogen content varies between 10% and 14%. In addition, small amount of elements such as nitrogen, oxygen, sulfur and metals (i.e. Ni and V) are found in crude oils. The SARA-separation is an example of such group type analysis, separating the crude oils in four main chemical classes based on differences in solubility and polarity. The four SARA-fractions are the saturates, aromatics, resins, and the asphaltenes (Aske, 2002). Among them, asphaltene is viewed as the most polar and highest molecular weight fraction of the crude oil. Asphaltene can be defined as the fraction separated from crude oil or petroleum products upon addition of hydrocarbon solvents such as *n*-heptaneand soluble in aromatic solvents such as toluene or benzene (Speight, 1999). The chemical structure of asphaltene is very complex and it has been the subject of many studies (Tharanivasan, 2012). A common problem faced by the oil industry is the deposition of asphaltene that can occur inside production wells, storage and refinery vessels, surface facilities and transfer pipelines (Escobedo and Mansoori, 2010; Ferworn et al., 1993; Jamialahmadi et al., 2009; Nielsen et al., 1994). Deposition of asphaltenes also can reduce well productivity, damage pumps, restrict or plug flow lines and pipelines and foul production handling equipment (Tharanivasan, 2012). Asphaltene precipitation is a thermodynamic process which is mainly a function of pressure, temperature, and fluid composition. When crude oil comes from reservoirs with high pressure into the oil column, due to pressure drop, asphaltenes precipitate and eventually deposit on the interior surface of flow lines. Typically, the amount of precipitated asphaltenes increases as the pressure decreases and reaches a maximum at the bubble-point pressure. Asphaltene deposition, on the other hand, is a much more complex process and also depends on flow shear rate, surface type and characteristics, particle size, and particle-surface interactions. Therefore, the tendency of the crude oil to form solid particles should be studied and modeled (Akbarzadeh et al., 2011a). There are two common approaches for solid deposition determination: Eulerian and Lagrangian (Guha, 2008). The Lagrangian schemes involve trajectory

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Nomenclature

Abbreviations

CFD	computational fluid dynamics
DRW	discrete random walk
RANS	Reynolds-Averaged Navier-Stokes
SARA	saturates- aromatics- resins- asphaltenes

Variables

A	pipe cross-sectional area
C_∞	bulk concentration
C_D	drag coefficient
D	pipe diameter.
d_p	particle diameter
f	Fanning friction factor
F	forces acting on the particles
F_G	net gravitational force
F_v	volume forces
g	gravitational acceleration
J	particle mass flux
k	turbulence kinetic energy
k_B	Boltzmann constant
k_s	mean microscale roughness
L	length of pipe
m	particle mass
N_i	number of entering particles
N_o	number of exiting particles
P	pipe perimeter
P_k	production of turbulence
R	gas constant
Re	fluid Reynolds number
Re_p	particle Reynolds number
T	absolute temperature
T_s	well surface temperature
$\overline{U}$	time average fluid velocity
u^*	flow shear velocity
u'	fluctuating velocity component
u	fluid velocity
u_{ave}	average fluid velocity in the axial direction
V_d^+	dimensionless deposition velocity
V_{pi}	particle velocity
V_d	particle deposition velocity
z	pipe axial direction
p	pressure

Greek letter

v	kinematic viscosity
μ_T	turbulent eddy viscosity
ρ_p	particle (asphaltene) density
τ_p	particle relaxation time
S_p	sticking probability
k_d	constant
E_a	activation energy of adhesion
μ	fluid dynamic viscosity
Δt	time step
ζ	Gaussian random number
ω	specified dissipation rate
ρ	fluid density

calculations where the instantaneous motions of individual particles are tracked by solving their equations of motion (Kallio and Reeks, 1989). In the Eulerian approach often called a two-fluid model the particles are treated as a continuous phase, in much the same way that a tracer fluid would be regarded in a binary mixture. The motion of the particulate phase is mathematically described by mass, momentum and energy conservation, similar to fluids (Hossain et al., 2006). Some studies have been performed to simulate asphaltene deposition on interior wall of pipeline, wellbore and well tubing using different approaches. Kabir et al. applied heat transfer models for investigating deposition of hydrocarbon solids in wellbore (Kabir et al., 2002). They studied fluid flow characteristics and fluid thermodynamics behavior to minimize solid deposition through controlling pressure and temperature profiles in the wellbore. The model was applicable for paraffinic and asphaltic oils. Ramirez-Jaramillo et al. used molecular diffusion mechanism for modeling of asphaltene deposition in well column. They assumed that the particle concentration gradient is caused by the temperature gradient at the pipeline wall (Ramirez-Jaramillo et al., 2006). This assumption was later criticized by other researches (Eskin et al., 2012; Paes et al., 2015). According to Eskin et al. (Eskin et al., 2012) and Paes et al. (Paes et al., 2015), contrary to wax deposition the deposition of asphaltene was very limited influenced by temperature variation. Soulgani et al. (Soulgani et al., 2009) suggested a model for description of asphaltene deposition process in wellstring. They assumed that the deposition on the tubing surface is controlled by the chemical reaction mechanism in which the asphaltene deposition was estimated using Arrhenius like equation. The possibility of asphaltene deposition in deepwater oil pipelines was studied by Chen et al. (Chen et al., 2010). The main factors affecting asphaltene deposition was considered in oil pipelines. The results showed that the stability of asphaltene can be monitored by analyzing the changes in the main parameters such as temperature, pressure, and oil composition. Vargas et al. proposed a model which includes the sub-models describing the particle precipitation, agglomeration, transport, and deposition on the wall (Vargas et al., 2010). In that work the aggregation and the deposition phenomena were modeled using pseudo-first-order reactions and the particle transport was described by the convection-diffusion equation. Otung and Osokogwu developed a computer application model based on the C++ language to predict wax precipitation and deposition in oilfield installations (Otung and Osokogwu, 2012). The designed computer program included transport and thermodynamics models for wax precipitation and deposition. The results showed that the model is capable for predicting wax appearance temperature as well as wax deposited thickness in comparison with experimental data. Asphaltene precipitation and deposition under flowing conditions was experimentally studied by Seifried et al. (Seifried et al., 2013). They conducted set of asphaltene deposition experiments in capillary flow. According to the experimental results, higher flow rate of injected oil led to a higher deposition rate and a higher mass of deposited asphaltenes on the tube surface. Akbarzadeh et al. developed a model of asphaltene deposition that is significantly different from the previous works (Akbarzadeh et al., 2011a, 2011b). According to the model of Akbarzadeh et al., the deposition occurs as follows: asphaltene particles precipitate and then grow in a flow due to agglomeration. They assumed that the particle concentration is uniform over a pipe cross section and the particles are transported to the wall, being involved in random fluctuations caused by both the Brownian motion and turbulence, and also by turbophoresis.

Despite the works devoted to modeling of asphaltene deposition, the large size asphaltene aggregates that are of high inertia effect have not been well considered. The studies demonstrated that once the asphaltenes precipitate, i.e. asphaltenes separate from a crude oil, due to sticking of asphaltene monomers with each other the aggregates form and grow (Branco et al., 2001; Ferworn et al., 1993; Nielsen et al.,