MODELING OF ASPHALTENE DEPOSITION IN PIPELINES

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ABSTRACT

This paper is concerned with asphaltene deposition in fluid flowing through pipelines. Brownian diffusion and drag, gravitational, thermophoresis, buoyancy, and shear removal are considered as possible mechanisms in the asphaltene deposition process. The thermo-physical properties of the fluid were obtained from Iranian oil fields. A model was used in the pipeline deposition modeling to predict the asphaltene deposition rates under flow conditions. The effects of particle size, temperature gradient, and fluid velocity were studied on asphaltene deposition rate. The results showed that, among the above-mentioned mechanisms, the gravitational and thermophoresis forces played a significant role in the formation of the deposit under the flow conditions. To verify the model, some predictions were compared with the available aerosol deposition data in the literature.

Keywords: Asphaltene deposition, Drag, Thermophoresis, Buoyancy, Shear Removal

INTRODUCTION

The deposition of asphaltene on a pipe surface in oil flow is commonly encountered in petroleum industrial processes. Asphaltene is a polydisperse mixture of the heaviest and most polarizable fraction of the oil. Due to the tendency to precipitate and deposit, asphaltene causes many problem in oil production, transfer, and storage. Several researchers have investigated the asphaltene deposition problems under dynamic conditions, i.e. during the oil flow. Mansoori has studied the factors affecting the heavy organic deposition such as asphaltene in the well-head production of petroleum [1]. He proposed a model which considered four different effects (mechanisms) on asphaltene depositions including polydispersivity, steric colloidal, aggregation, and electrokinetic effects. Only one of these mechanisms, namely electrokinetic effect, is of great importance during oil transportation. The other factors are considerable under the static (stationary) conditions of petroleum fluid. The electrokinetic effect rises due to streaming potential generated by the flow of charged solid particles such as asphaltene. Mansoori showed that when the oil entered pipelines, positively charged asphalttene particles began to become attached to the pipe wall [1]. As the negatively charged oil flows toward downstream, the charge difference between wall and bulk fluid grows and leads to creating a potential difference. This potential difference causes the asphaltene particles to flow backwards and hence the probability of

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their deposition increases. To demonstrate the existence of electrokinetic effect, Mansoori used the static phase diagram of some oils and did not apply any data for the dynamic deposition of asphaltene [1].

Ramirez-Jaramillo et al. have investigated the asphaltene deposition in production pipelines via a multiphase multicomponent hydrodynamic model [2]. They assumed the radial diffusion of asphaltene particles with two competing mechanisms: molecular diffusion and shear removal. To validate their model, Ramirez-Jaramillo et al. used available data of pressure-temperature-depth production profiles related to asphaltene deposits in two problematic wells from the southwest producing area of Mexico [2]. They used these data to predict the thickness of deposited asphaltene layer as a function of the axial coordinate for different oil flow rates. The results indicated that the wells presented the formation of asphaltene deposit located at various depths.

Escobedo and Mansoori studied the mechanism of the migration of suspended heavy organic particles towards the walls in oil-producing wells and pipelines [3]. They proposed an analytical model for calculating particle deposition coefficient under the conditions of petroleum fluids flowing in oil wells. They used eddy diffusivity, Brownian diffusivity, as well as inertial effects to develop their model. This model was able to predict the rate of particle deposition during various turbulent flow regimes. They compared the predictions of the proposed model with the available experimental data. Since experimental data for particle deposition from petroleum fluid flows were scarce, they used the deposition data from aerosols (deposition rates for aluminum and iron particles in air) to verify their model. The modeling results were in very good agreement with the experimental data. It was also shown that deposition rates decreased with increasing particle size. Eskin et al. analyzed the deposition mechanism of asphaltene in pipelines based on the theoretical and experimental approaches [4]. Their model consisted of three mechanisms for modeling particle transport to the wall, namely Brownian motion, turbulent diffusion, and turbophoresis. They also used the special Couette device to simulate asphaltene deposition in pipeline and tubing wells. In their experimental setup, Eskin et al. measured the mass of asphaltene deposits at the different running times [4]. These results were used to calculate the model parameters, such as critical particle size, particle-particle collision efficiency and particle-wall collision efficiency. This model was then used to determine the distribution of the thickness of the asphaltene deposit layer along vertical production tubing. The results showed that only particles which were smaller than a critical size were able to deposit.

In the previous proposed models, turbulent flow parameters were considered, but the most important mechanisms which had a crucial role in the asphaltene deposition of a laminar flow were not addressed. Also, in those models, the asphaltene deposition rate was not considered. In this paper, a theoretical model is developed to predict the asphaltene deposition velocity during fluid flow in pipelines. The proposed model takes into account the effects of main mechanisms such as Brownian diffusion and drag, gravitational, thermophoresis, buoyancy, and shear removal which influence the asphaltene deposition phenomena.

THEORY

Asphaltene Deposition Model

Many factors affect the asphaltene deposition phenomena in the petroleum fluids flow. Generally, in every flow regime (laminar or turbulent), it is always possible to find a narrow layer (the viscous or laminar sublayer) of fluid near the wall. Within this layer, the dominating transport mechanism is molecular diffusion. In the center, on the other hand, the transport mechanism depends upon flow regime and the distribution form of momentum, heat, and mass species. In the case of a laminar flow regime, the aforesaid distributions are obtained using governing equations of motion, heat, and mass in fluid flow; however, in a turbulent flow, a complex set of equations must be solved for predicting momentum, heat, and mass species profiles [5].

Herein, it is assumed that the turbulence effects on fluid flow are negligible. Under these conditions, the asphaltene deposition occurs under the influence of some significant mechanisms such as Brownian (molecular) diffusion, drag, gravitational, thermophoresis, buoyancy, and shear forces deposition. The role of different mechanisms affecting the asphaltene deposition phenomena depends on many parameters such as temperature, fluid velocity, asphaltene particles size, etc. These mechanisms and their formulations are described below.

Brownian Diffusion

Brownian motion is the apparently random motion of small particles when suspended in a fluid. The molecules strike the suspended particles and exert a small force on them as a consequence. If the particles are small enough, the force on the particles as a result of these collisions is sufficient to produce observable motion. Because of the random motion of the particles, they diffuse from the regions of high concentration to the regions of low concentration. Here, this diffusion is called Brownian diffusion. In the crude oil-asphaltene system, the collisions between the asphaltene particles and oil molecules lead to the random Brownian motion of suspended asphaltene particles and because of this random motion, the asphaltene particles diffuse in the fluid. The asphaltene mass flux due to Brownian diffusion is calculated by Fick’s law:

$$J_B = -D_B \frac{\partial C}{\partial r} \quad (1)$$

where, J_B is the Brownian diffusive asphaltene flux in the radial direction, $\partial C/\partial r$ is the radial gradient in asphaltene concentration and D_B is the asphaltene Brownian diffusivity coefficient. The Brownian diffusivity can be calculated by the Stokes-Einstein relation [6]:

$$D_B = \frac{k_b T}{3\pi\mu d_p} \quad (2)$$

where, k_b is the Boltzmann constant (1.38×10^{-23} J/K); T stands for the absolute temperature; μ and d_p represent the absolute viscosity and the asphaltene particle mean diameter respectively. According to the Pilat and Prem's work, the Brownian force can be expressed as the following equation [6]:

$$F_{Br} = \frac{k_b T u_p}{D_B C_c} \quad (3)$$

where, u_p is the particle settling velocity and C_c stands for the Cunningham correction factor, which can be estimated by the expression:

$$C_c = 1 + K_n \left[1.257 + 0.4 \exp\left(-\frac{1.1}{K_n} \right) \right] \quad (4)$$

where, $K_n = d_p/\lambda$ is the Knudsen number and λ represents the mean free path of molecule. According to the kinetic theory, λ is expressed as [7]:

$$\lambda = \frac{k_b T}{\sqrt{2}\pi d_p^2 P} \quad (5)$$

where, P is pressure.

Gravity Force

The higher mass density of the asphaltene particles with respect to oil (about 1.2 gr/cc) causes the settlement and deposition of the asphaltene particles in a gravity field. The gravitational force acting on asphaltene particles may be given as:

$$F_g = \rho_p g V_p \quad (6)$$

where, V_p and ρ_p are the particle volume and density respectively and g is the acceleration of gravity (9.8 m.s^{-2}).

Shear Induced Lift Force

Due to shear effects, the dispersed asphaltene particles in the oil phase experience a lift force which is applied perpendicular to the direction of flow [8]. The magnitude of this shear-induced lift force on asphaltene particles can be calculated using Saffman equation [9, 10]:

$$F_l = \frac{1.62 \mu d_p^2 \left(du/dr\right)}{\sqrt{\nu \left|du/dr\right|}} \left(u - u_{px}\right) \quad (7)$$

where, u is the fluid velocity; du/dr is the fluid velocity gradient (shear strain) and u_{px} represents the asphaltene particle velocity in the axial or x-direction; d_p, μ, and v are particle diameter, fluid absolute, and kinematics viscosities respecttively.

Thermophoresis

Thermophoresis, thermodiffusion, or Soret effect (or Ludwig-Soret effect) is a phenomenon observed when a mixture of two or more types of motile particles (particles able to move) is subjected to the force of a temperature gradient and the different types of particles respond to it differently [8]. In the presence of temperature gradient in asphaltene-oil fluid flow in pipelines, thermophoresis can affect the motion of dispersed asphaltene particles. This force is the reason for asphaltene movement from hot toward cool regions. This force can be evaluated by applying the following equation [11]:

$$F_{th} = -\frac{3\pi\mu^2 d_p H}{\rho_a T_p} \frac{dT}{dr} \quad (8)$$

where, $\frac{dT}{dr}$ is the radial temperature gradient; T_p and H are the absolute temperature of particles and the thermophoretic force coefficient, which can be calculated by Equation 9:

$$H = \left(\frac{2.34}{1+3.42\,K_n}\right)\left(\frac{k_f/k_p + 2.18\,K_n}{1+2k_f/k_p + 4.36\,K_n}\right) \quad (9)$$

where, K_f and k_p are the thermal conductivities of the fluid and the asphaltene particle respectively.

Drag Force

Drag refers to forces that oppose the relative motion of an object through a fluid (a liquid or gas). This force acts in a direction opposite to the oncoming flow velocity. In the general case, the drag force exerted on a particle moving along with a fluid is calculated by Equation 12 [12]:

$$F_D = \frac{\pi d_p^2 \rho_f \left(u_r - u_p\right)^2 C_D}{8 C_c} \quad (10)$$

where, u_r is the r-component of fluid velocity and C_{Di} stands for the drag coefficient.

Buoyancy Force

According to Archimedes law, when an object is immersed in a fluid, it displaces the same volume of the fluid as the immersed volume of the object and is consequently buoyed up by a force equal to the weight of the displaced fluid. The buoyancy force is obtained by the following equation:

$$F_{buoy} = \rho_f g V_{ip} \quad (11)$$

where, g the gravity acceleration and V_{iP} is the immersed volume of particle.

MODEL EXECUTION

The applicability of the proposed model is examined in a pipe with inner radius of r_i and length of L. The hydrocarbon mixture flowing in the pipe contains asphaltene particles with a concentration of C_0 at the beginning of the pipe (L=0) and C at the arbitrary pipe length of x. The initial temperature, pressure, and velocity of hydrocarbon mixture are T_i, P_i, and u_i respectively. Due to various deposition mechanisms, asphaltene can be deposited on a pipe surface and the asphaltene concentration of hydrocarbon mixture is reduced at the pipe exit. Figure 1 shows deposition asphaltene on the inner surface of a pipe.

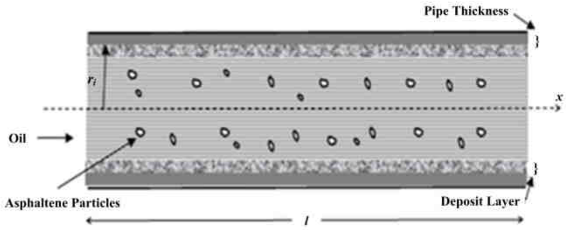

Figure 1: Schematic of asphaltene deposition on a pipeline surface

The original fluid contains some dissolved asphaltene and perhaps some dispersed colloidal particles of the asphaltene. Changes in temperature, pressure, and compositions are the main causes of the asphaltene precipitation. At first, the precipitated particles are dispersed in fluid. Thereafter, other factors such as particle tendency to adhesion, the size of particles, the conduct characteristics, and the fluid flow behavior can control the asphaltene deposition process. The settling (deposition) velocity of asphaltene is obtained via balancing between different forces acting on the flowing asphaltene particles in the pipe. Brownian diffusion is significant for very small particles (d_p<0.1 μm), but has a negligible effect on the large asphaltene particles with the size considered herein (d_p=0.5-100 μm). Hence, herein, the effects of other dominating forces, namely gravity settling, shear induced lift force, thermophoresis force, drag, and buoyancy force are considered.

The motion of asphaltene particles from bulk phase toward pipe surface can be intensified or weaken by different effective forces. For example, forces such as buoyancy, drag, and lift are opposed to asphaltene deposition on surface and hence decelerate the effect of the others. On the other hand, a force such as gravity is in accordance with deposition direction and thus accelerates the deposition process. Some forces such as thermophoresis force have a double effect depending on flowing fluid temperature whether it is higher or less than wall temperature. For a hot wall, heat is transferred toward fluid and as a result decelerates the asphaltene deposition; however, in the case of a cold wall, thermophoresis force and deposition velocity has the same direction and therefore the asphaltene deposition is intensified.

Force Balance on the Whole Deposit

Among the mechanisms previously discussed, gravity deposition and thermophoresis force help the deposit grow while shear removal, buoyancy, and drag forces do the opposite. Therefore, a total force balance on the whole deposit can be written as follows:

$$F_g \pm F_{th} - F_{buoy} - F_l - F_D = m_p \frac{du_p}{dt} \qquad (12)$$

By replacing F_D from Equation 10 into the above equation with an assumption that u_r=0, the following expression is derived:

$$F_g \pm F_{th} - F_{buoy} - F_l - \frac{\pi d_p^2 \rho_f C_D}{8 C_c} u_p^2 = m_p \frac{du_p}{dt} \qquad (13)$$

u_p is the deposition velocity of asphaltene particles, which can be obtained by solving the above equation. The maximum attainable velocity of asphaltene particles is called the terminal velocity and, under these conditions, the particles reach a constant deposition velocity. The terminal velocity of the asphaltene deposition can be evaluated from Equation 14:

$\left(\frac{du_p}{dt} = 0\right)$:

$$u_p = \left(\frac{8C_c \left(F_g \pm F_{th} - F_{buoy} - F_l \right)}{\pi d_p^2 \rho_f C_D} \right)^{0.5} \qquad (14)$$

In this equation, u_p is the deposition (settling) velocity of asphaltene particles, which depends on many different variables. To estimate the unknown parameters, we assume that the oil is flowing inside the pipe with a diameter of 50 cm and a length of 100 m. The fluid velocity as well as its temperature profile is supposed parabolic in the radial direction. In addition, it is assumed that the temperature changes linearly during the axial direction.

Table 1 shows the concerned parameters of the fluid and asphaltene used in this work [14].

Table 1: Characteristics of the Fluid under Study

Parameters	Oil	Asphaltene
$\rho\ (kg.m^{-3})$	860	1200
$Cp\ (J.kg^{-1}.K^{-1})$	213	920
$K\ (W.m^{-1}.K^{-1})$	0.120	0.75
$\mu\ (Pa.s)$	0.075	-
$\alpha = \frac{K}{\rho\, Cp}\ (m^2.s^{-1})$	6.55×10^{-4}	6.79×10^{-7}

RESULTS AND DISCUSSIONS

Asphaltene Particle Size Effect

As it can be expected, asphaltene particle size plays a main role in the deposition velocity. To establish a fact of this claim, the asphaltene particle size is assumed to be in the range of 0.5 to 100 micron [15-17]. Equation 14 quantifies the effect of asphaltene particle size on its deposition velocity. The results are depicted in Figure 2.

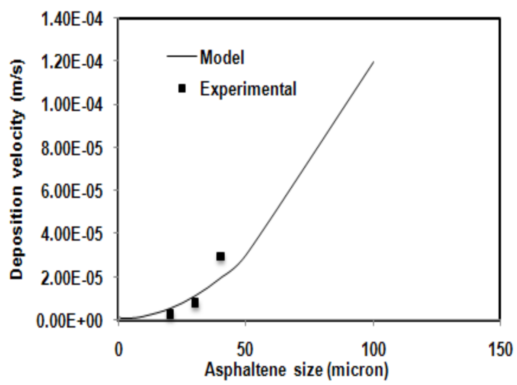

Figure 2: Effect of asphaltene particle size on deposition velocity

As shown in the figure below, increasing the asphaltene particle diameter causes a rise in deposition velocity. Since experimental data for asphaltene deposition from petroleum fluid flow were scare, the verification of the model was accomplished using some available aerosols deposition data [3]. As it is shown, the model predictions are in good agreement with deposition data.

It is also shown that among the mentioned forces, the gravitational force is more affected by particle size variation. This is due to the cubic relation of this force to the particle diameter. The concerned results are shown in Figure 3.

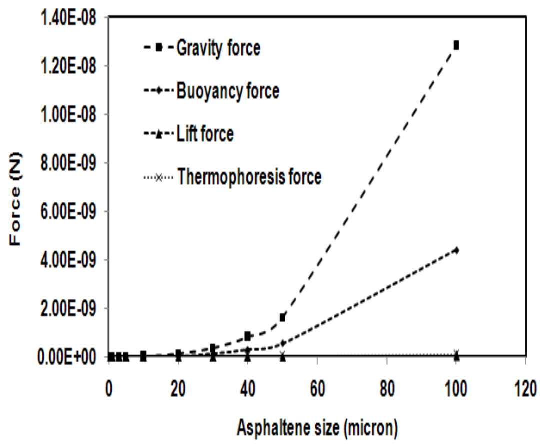

Figure 3: Effect of asphaltene size on the magnitude of different forces

Temperature gradient between fluid and pipe wall causes heat transfer phenomenon. This phenomenon can influence the thermophoresis force which is one of the forces for asphaltene deposition. Depending on temperature gradient direction, deposition velocity may be increased or decreased. While the wall temperature is higher than the fluid bulk temperature, heat flows from the wall toward the fluid bulk. This leads to a decrease in asphaltene deposition rate; this is due to thermophoresis force which acts in the direction of temperature gradient.

On the other hand, in the case of a cold wall the temperature gradient, thermophoresis force, and deposition velocity has the same direction and therefore the asphaltene deposition is intensified. Figure 4 shows the effect of temperature gradient on asphaltene deposition velocity. As depicted in this figure, the deposition velocity of asphaltene particles rises by increasing temperature gradient.

Fluid Velocity Effect

Fluid velocity is one of the main parameters affecting the asphaltene deposition phenomena. Changes in velocity influence the temperature gradient which is the major cause of thermophoresis force. Furthermore, the velocity variations have crucial effects on the lift force which can delay the asphaltene deposition.

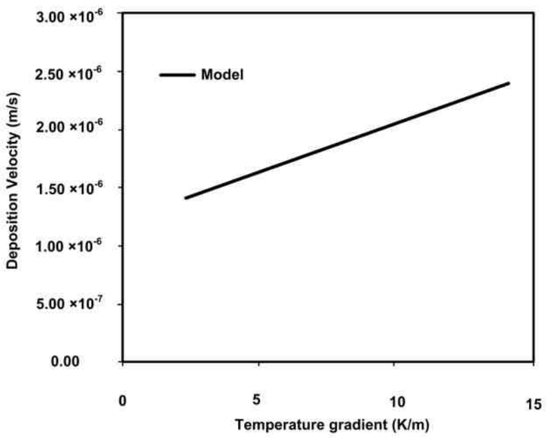

Figure 4: The effect of temperature gradient on deposition velocity

Figure 5 shows the effect of fluid velocity on both thermophoresis and lift force. The results of this work show that the fluid velocity affects the thermophoresis force more effectively than the lift force. Therefore, according to Equation 14, the deposition velocity rises as the fluid velocity is increased. The results obtained from velocity effect investigations are shown in Figure 6. The results obtained from our model are compared with some experimental aerosols deposition data [3]. According to Figure 6 there is a good agreement between the calculated and limited experimental data.

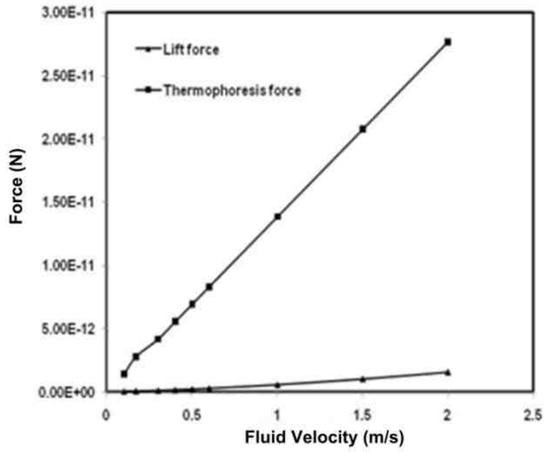

Figure 5: The effect of fluid velocity on forces

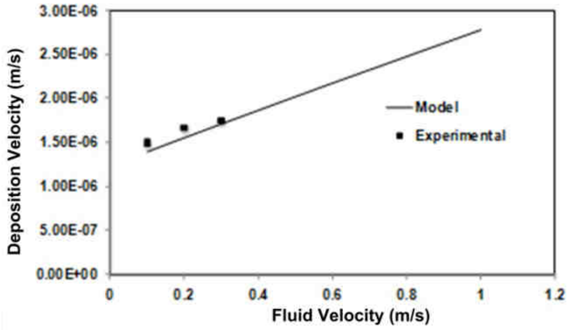

Figure 6: Effect of fluid velocity on deposition velocity

Asphaltene Concentration Changes

The deposition of asphaltene particles on pipe surface causes a significant variation in its concentration in the fluid bulk. The amount of deposited asphaltene can be estimated using a material balance around the inlet and outlet of pipe. For this reason, it is necessary to calculate the amount of asphaltene concentration at the pipe exit. The relation between particle concentration and its deposition velocity in a pipe flow was suggested elsewhere [13]. This equation is applied for the proposed system:

$$C = C_0 \exp\left(-\frac{u_p}{u}\frac{x}{R}\right) \tag{15}$$

where, u_p is the particle deposition velocity; u is the flow velocity; C and C_0 are the particle concentration in the x-direction and the particle concentration at the inlet of the pipe respecttively; R stands for the pipe radius. We assume that the hydrocarbon mixture contains an initial concentration of asphaltene particles equal to 0.05 *gr/cc*. Setting *x*=*L* under different conditions, the asphaltene concentration at the end of the pipe can be calculated using Equation 14. Since the asphaltene deposition velocity is affected by many different parameters such as particle size, fluid velocity, and temperature gradient, the asphaltene concentration is also changed by those parameters. The effects of some mentioned parameters on asphaltene concentration are investigated and the obtained results are depicted in Figures 7, 8 and 9.

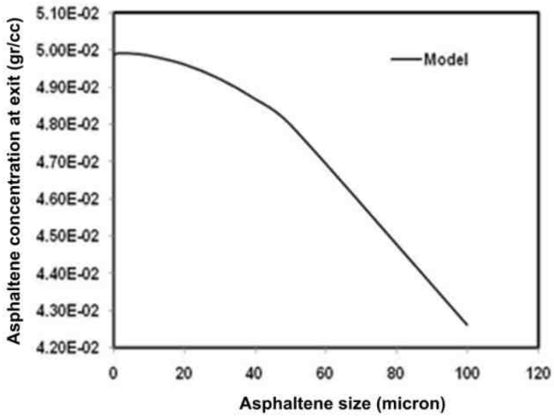

Figure 7: Effect of asphaltene particles size on the exit asphaltene concentration

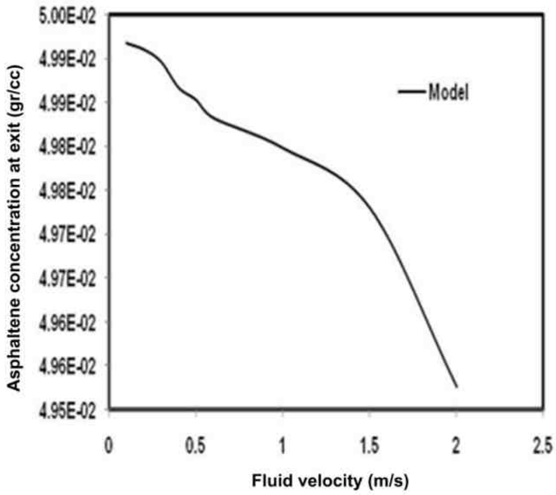

Figure 8: Effect of fluid velocity on asphaltene exit concentration

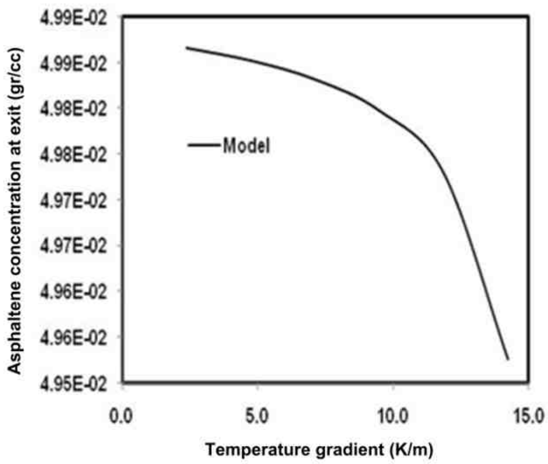

Figure 9: Effect of temperature gradient on asphaltene exit concentration

CONCLUSIONS

A new dynamic model is introduced for asphaltene deposition. The basis of this model is the contribution of different forces which act on the dispersed asphaltene particles in the petroleum fluid flow. The results show that the gravitational force is more affected by the asphaltene particle size in comparison with the other contributed forces; consequently, the deposition velocity rises by increasing asphaltene particles size. Also, the thermophoresis force, which is resulted from the temperature gradient between fluid bulk and the pipe wall, is exerted on the asphaltene particles. The results of this work show that the deposition velocity increases by a rise in the temperature difference between the fluid bulk and the pipe wall; the major reason is the existence of thermophoresis force, which is intensified by the temperature gradient increment. In addition, the results show that both the thermophoresis and lift forces are affected by the fluid velocity. Furthermore, the results show that the deposition velocity increases with a rise in fluid velocity. On the basis of the limited experimental data on aerosol deposition, the proposed model is able to predict the asphaltene deposition velocity in petroleum fluids flowing in pipes.

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