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Experimental Study and Dynamic Pore Scale Modelling of Asphaltene Precipitation in Porous Media

Abbas Khaksar Manshad[1,4], Ali Nikooey[2], Siavash Ashoori[2], Amir H. Mohammadi[3*], Rasoul Hassanalizadeh[3], Jagar A. Ali[4]*

[1] *Department of Petroleum Engineering, Abadan Faculty of Petroleum Engineering, Petroleum University of Technology (PUT), Abadan, Iran*
[2] *Department of Petroleum Engineering, Ahwaz Faculty of Petroleum Engineering, Petroleum University of Technology (PUT), Ahwaz, Iran*
[3] *Discipline of Chemical Engineering, School of Engineering, University of KwaZulu-Natal, Howard College Campus, King George V Avenue, Durban 4041, South Africa*
4 *Department of Petroleum Engineering, Faculty of Engineering, Soran University, Soran, Kurdistan Region-Iraq*

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Abstract

Asphaltene precipitation in the porous environment is one of the important problems that redeuces the oil reservoir's productivity. In this work, we re-visited several experimental works which have been designed and performed to obtain the permeability declination in a slim tube. By using a slim tube packed with glass beds as a synthetic porous medium and under different conditions this modeling has been performed. At different temperatures, various injection rates and oil to solvent volume ratios studied under different flood test experiment. In this study, single phase flow of oil in the slim tube using a dynamic pore scale network model was simulated, and a mathematical model was developed for matching an experimental data. The results obtained from various simulations of network model were compared to those data which have been achieved experimentally. The current model is based on the theory of deep bed filtration as well as an introduction of the relationship of initial and damaged permeability as a function of porosity change which was caused by deposition of asphaltene on the experimental setup. To simulate the porous medium under the experimental condition in order to estimate the value of the inclination of permeability. There is a good agreement between obtained experimental data and model results which shows the quality of the model.

Keywords: *Asphaltene precipitation; Slim-tube; Permeability reduction; Porosity; Network model.*

1. Introduction

Asphaltene precipitation and deposition can be decreased by means of different processes (mechanical, electrical or chemical) which are capable of elimination or decreasing colloidal particles leading to asphaltene deposition [1]. There are plenty of experimental efforts regarding asphaltene precipitation and deposition. Developed models with respect to asphaltene precipitation prediction can be categorized into two main groups of scaling rules and thermodynamic studies [1].

Network based models consider the connectivity to represent the macroscopic level of the porous medium with acceptable results. Consequently, to calculate the macroscopic properties of the network, Percolation theory needs to be employed [2].

The earliest works on this subject [3-4] determined algorithms in 2D or 3D networks of the porous medium. The models are capable of simulating the porosimetric curves, which apply the theory of percolation to calculate the absolute permeability.

There are available literature works [5] that include phase saturation calculation and relative permeability in the multiphase flow. The established algorithm cannot satisfy the relative permeability and saturation as it does for absolute permeability.

Leontaritis [6] developed an asphaltene near-well formation damage model to investigate the degree of formation damage resulted from deposition of asphaltene considering the time and the effect of asphaltene deposition on hydraulic of near wellbore region as well as wellbore itself.

Pore scale network model developed by Blunt *et al.* [7] is suitable for asphaltene precipitation simulation of two-phase flow. They used the experimental data obtained for the relative permeability of oil and water. In addition, it consists of some results for capillary pressure obtaining from network model. They treated the mentioned data with a BOAST simulator (a simulator of black oil in three phase, three-dimensional environment) which is developed and released by US energy department.

Current work includes a network model employed which aims to simulate asphaltene deposition effect on absolute permeability at the micro scale. In this model, flow through the pore bodies is assumed laminar. It represents a linear response between flow and pressure drop from a pore to the throat. Accumulation of the fluid inside a single element is neglected which shows the inability of the model to capture all of the effects including unusual behavior in higher Reynolds numbers. The driving force to move the fluid from pore to throat is considered to be the pressure difference between the throat and pore centers.

1.1. Asphaltene precipitation fundamentals in a porous environment

The three main sources of colloidal particles in crude oil, which can initiate the asphaltene deposition, are as follows:

1. Contamination of the system during injection of the fluids to the reservoir, work over and the methods which are prevalent in recovery interests.
2. Incompatible materials injected into the reservoir, can interact with rock and mobilize the forming particles.
3. Chemical reactions, as well as organic and inorganic precipitation, can produce particulates.

Four initial mechanisms to migrate the several fine particles along with the flow of the fluid are as follows: [8-9]: penetration, adsorption, precipitation and sedimentation,and Fluid forces.

Asphaltene deposition near to the wellbore can be caused by different parameters including filtrate with high pH and injecting the fluid with low surface tension (e.g., diesel, light alkanes C5-C6 and gas condensates) to the reservoir [10]. During the acidizing process, low pH acids can form which would probably help forming asphaltenic or paraffinic sludge [10].

During petroleum production process, organic deposits can form in the different parts of the plant including reservoir, pipelines, and well. Asphaltene, wax, and resins are the typical and primary sources for the sediments. For the organic sediments, the upper section of the producing well is favorite parts to start deposition. As the asphaltene forms, pressure would drop to below asphaltene fluctuation point, and this will guide the deposition process toward the next parts of the well. This gradual progress would continue until the organic sediments reach to the wellbore and start to form in that zone [11]. Especially, in the reservoirs, which contain large specific area clays (e.g., kaolinite) the initial adsorption and retaining of the polar resins and asphaltenes are very quick [11]. Consequently, molecular deposits (multi-layer arrangement) will sediment close to the surface area of the pores [12.] Regardless of the large aggregate size of the formed asphaltene from suspended sediments in the oil phase, it is impossible for them to pass the pore and they will trap inside the throat [11]. Plugging in the pore throat intense problem on permeability as it closes the passages between the throats. The blockage will intensify the in-situ cake growth under very small remaining flow in to the jammed zone.

Because of deformability and stickiness of the deposits, they normally make sealing on flow constrictions. However the pore space is not completely blocked, it leads to diminishing the flow path conductivity [13-16]. Leontarities [6] emphasizes the asphaltene deposition as the ini-

tial cause of the organic damage. The organic deposition will probably widen the rage of its effect by growing toward the wellbore which more noticeable during the miscible recovery. The deposition initiated from wax deposition does not extend more than 0 to 1 feet, which occurs from pressure loss and cooling the oil during the production of oil.

Minssieux [11] illustrated the same behavior of permeability reduction caused by colloidal particle immigration while there is a running injection of the brine. He conducted several experiments on different porous media, which led to the aforementioned results. Therefore, to study and interpret the obtained results from the tests, a different model was employed to investigate the data. Because of the lack proper experimental data in this regard, it is necessary to conduct experimental studies using different particulates including water and polymers to investigate the mechanism in association with asphaltene deposition in the porous environment.

1.2. The physics of permeability damage

Roque *et al.* [17] conducted comprehensive experiments on Quartzite porous stone and prior to measurements characterized the sample very well. With an aim to investigate the effect of different parameters including operating parameters, flow rate, concentration and particle size on the permeability of the porous medium was investigated. The obtained result shows the importance of those parameters especially due to the deep condition that precipitation needs to be considered. The results are briefly provided in Figures 1 and 2. In Figure 2, the dashed line shows the effect of initial concentration on the concentration of the particles. The solid lines represent the effect of permeability ratio on sedimentations. Experiments have shown that in sole phases, the particle retention is independent of its total effect on permeability. Considering permeability declination and deposition mechanism, the most important parameters are of the particle location as well as deposition kinetics. Further investigations have shown that the reduction of the permeability is highly dependent on the mechanism of the specific particle deposition.

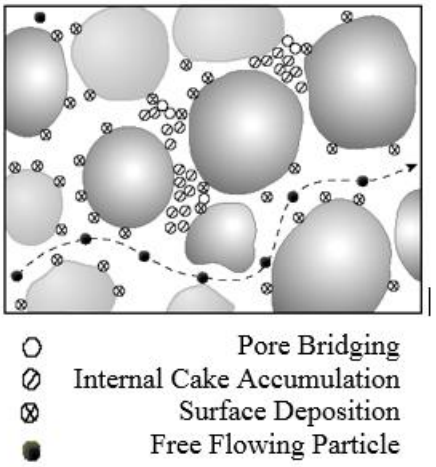

Fig. 1. Inter-pack damage mechanisms [17]

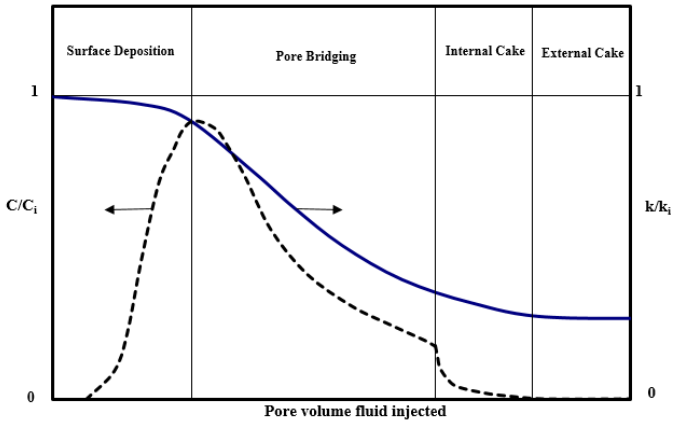

Figure 2. Phases of fines damage process and relative effects on permeability [17]

1.2.1. Particle surface precipitation

In surface precipitation, the deposition site is surface of the grain/pore. The difference of the electrostatic charge between the surface of the pore and particle, the texture of the pore surface and chemical properties and concentration of the pore play the main roles on the kinetics of the deposition process on the surface of the pore. Reduction of the permeability would be significant only if the deposition on the surface of the pore initiates on the throat of the pore.

Therefore, the effect of throat sediments fractions is more important than their quantity on permeability reduction. If the suspensions flow rate is stable, the surface deposition will become strictly mono layer due to strong repulsion between almost static particles. For this phase, the monolayer deposition would occur if the opposing energy of aggregation is high. Due to the results of experiments as well as theoretical sources, it can be concluded that the deposition on the surface has a minor effect on permeability reduction which is denoted in Figures 1 and 2. Small size particles (e.g., clay-size and colloidal) are the favorite species to follow the surface precipitation mechanism as the large particles are not available [18].

1.2.2. Bridging of pore throat

Bridging of pore throat is an issue as the particle makes bridge while attempting to pass the pore throat (shown in Figure 2). Bridging would be in either way of two particles (deposition of a flowing particle on a previously deposited particle) or three particle bridging (bridging of a flowing particle on two formerly deposited particles). Another condition, which can initiate the blockage, is a larger particle diameter in comparison with pore diameter. Obviously, it would possibly bridge with the mechanism of one particle bridging. Forming the bridge would block the pore throat leading to accumulation of the new arriving particles. It would decrease the flow rate in the result. The most significant permeability reduction belongs to this phase (as shown in Figure 2).

1.2.3. Internal cake formation

After bridging the throat to the critical state, it is not functioning in the network of the pores in the depth of damage. Thereafter, accumulation would intensify inside the pore throat and will infect the bodies of the connected pores to the flowing particles leading to initiation of the filter cake within the zone (as shown in Figure 1). The system permeability is controlled by the permeability of the damaged region and its depth. A rapid decrease in particle concentration of the downstream is an indicator of internal cake formation (denoted in Figure 2). Small particle distribution and concentration are the main factors influencing the amount of the damage on permeability.

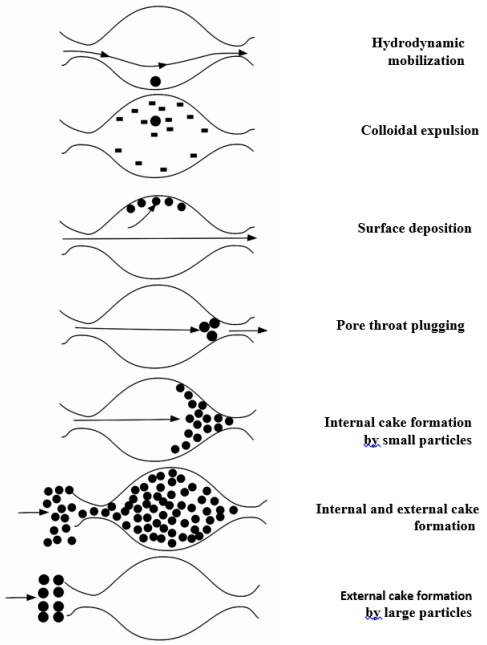

Fig. 3. Varions particulate processes [23]

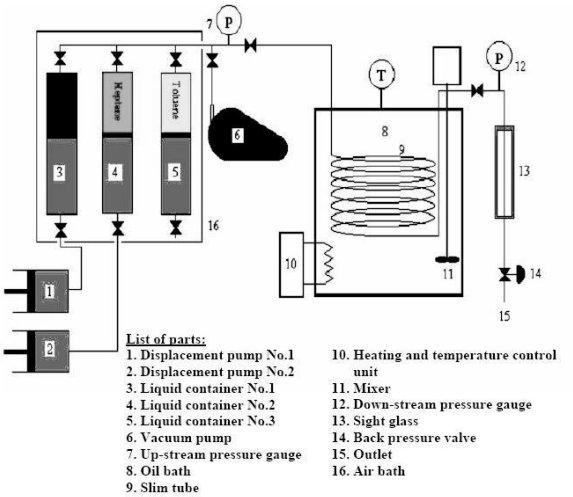

Fig. 4. A schematic diagram of the experimental setup

1.2.4. Formation of the external cake

Right after internal cake formation, the accumulation would move into the upstream and initiate the external cake formation (illustrated in Figures 2 and 3). Figure 3 shows the process of several particulates schematically.

2. Experimental section [22]

2.1. Materials and apparatus

By conduction of several experiments on synthetic porous medium, this phenomenon was studied. The main effort was to simulate the reservoir condition which includes high temperatures and pressures. The equipment is shown in Figure 4. It is made of a slim tube, situated inside an oil bath, a pump to evacuate the cell, and a pump to pump the liquid, a vessel to transfer the fluid, a transparent slim tube to monitor the behavior of the stream which is equipped to a jacket. The experimental equipment consists of a slim tube placed inside an isothermal oil bath, vacuum and liquid pumps, fluid transfer vessels; transparent capillary with a heating jacket that eases the monitoring while the fluid passes the tube, a regulator for the pressure, an oil collection flask, fittings, pipes and pressure gauges.

The mentioned tube is similar to the Ruska tube, which is suitable for determination of the quantity of the damage on permeability. It is a narrow tube made of stainless steel wrapped with a coil. External and internal diameters are 7.9 and 6.2 mm, respectively and coiling diameter is 200 mm. The tube is 18.3 meters long, which is packed using round glass packing.

The approximate porosity of the medium is 27%, and the absolute permeability is 4.93×10^{-12} m^2 (equivalent to five Darcies). The approximate pore volume of the system is 150 cm^3.

The isothermal bath with a volume of 60 liters, is controlled by a temperature controller which is adjustable either using a computer or manually. It can reach to 175°C. There is a designed duct to hold the circulating mixer and heating element to help to mix the fluid thoroughly and the equipment free from the bath with a space between them. The bath is equipped with an adjustable outlet, and inlet valves of the slim tube are connected to the top side of the bath. The tube is placed in a way that the whole tube is submerged into the bath to have a uniform temperature distribution. Downstream of the tube is connected to the transparent capillary that can hold up to higher pressures. It is equipped with a heating jacket to facilitate the monitoring of either one or two phase flow passing the tube.

Two pressure gauges are located in down and upstream sides of the tube to observe the pressure. To control the pressure, a backpressure regulator is placed, and thereafter the oil can be flashed to the atmospheric pressure. The pressure of the upstream can be monitored by employing a pressure gauge (the same regulator is connected to the downstream side).

The pumps are made of the cylinder-piston frame which can contain 500 cm^3. Its flow rate range can be varied between 1 to 2000 cm^3/hr. The pump has two cylinder and piston configuration (capacity of each cylinder is 500 cm^3). It operates up to 70 MPa which can work in either way of manual or computer adjustment.

The material is a crude oil sample from an oil field in the southern part of Iran. It was kept in laboratory condition for quite an appropriate period of time (3 months) to get rid of volatile components and reach a stable composition. Specifications of the sample are provided in table 1. Its gravity index is 20°API (heavy oil) with asphaltene content of 11-weight percentage. To eliminate the possible impurity produced together with crude oil such as sand and clay, it is filtered using Wattman number 42 standard filtrate. As a precipitant, n-heptane was used in the experimentals, and the measurement method to capture the deposited quantity was the gravi-metric method.

2.2. Experimental method

There are two main experimental methods, which include:

2.2.1. Preliminary activities

These series of activities consist of washing, drying and evacuating the tube, filing the vessel with fluid to transfer it, measurement of the pore volume, system behavior investigation, and measurement of the permeability and eventually applying the Carman-Kozny equation with respect to porosity calculations.

Table 1. Composition and characteristics of the crude oil [1, 21, 22]

Component	Mole fraction	Property	Value
H_2S	0.192	Reservoir Oil MW (g/gmol)	156.67
Nitrogen	0	Test temperature (F)	225
CO_2	2.204	MW C_{7+} (g/gmol)	316.49
Methane	26.945	SG C_{7+}	0.9272
Ethane	8.008	Density of reservoir fluid @ Pb (g/cc)	0.7646
Propane	6.426	Bubble point pressure (psia)	1890
i-Butane	1.134	Asphaltene content in stock tank oil, wt%	11
n-Butane	3.682		
i-Pentane	1.742		
n-Pentane	2.233		
Hexanes	4.202		
$Heptanes_+$	43.212		

2.2.2. Flooding experiments

The effect of the different parameters such as injection rate, temperature, permeability reduction and oil ratio was investigated by conducting series of experiments (flooding experiments). The precipitant was n-heptane in all of the flooding experiments in a porous medium. One of the objectives of the measurements was designed based on using Darcy's equation which requires low Reynolds number. Therefore, the rate of injection was taken equivalent to the Reynolds number of unity into the porous medium.

The preliminary activities were undertaken with the aim of concluding the operational conditions of the porous medium for the flooding tests. The flooding test can be done following the steps of:

1. Filling the vessel of the fluid transfer with the oil (filtered oil) and same for the other vessel with n-heptane.
2. To connect the top valves of the vessels to each other using a T-junction connection.
3. Connecting the pumps to both vessels at the desired flow rate and running the vacuum to evacuate the vessels from unwanted impurities such as air and moisture.
4. Connecting the T-junction (free port) to the evacuated porous medium's inlet. Note that the valve should be closed.
5. Introducing the fluids and mixing them should start. Activating the pump while the the valve of the porous medium is opened (note that it should be simultaneously). After his point, time for any action needs to be recorded.
6. Recording the entrance valve pressure after the proper fixed amount of time (for example 2 minutes). Passing the mixture through the porous environment. The injection should be continued up until the time that the filled volume reaches to 150 cm^3 (one pore volume). The indication of the filled pore volume is pressure rising. This is the point that the outlet valve needs to be opened and consequently, inlet pressure starts to decrease, and in a very short time, it reaches to equilibrium condition (steady state). Asphaltene starts to deposit, and it increases the pressure of the medium. A sample of 10 cm^3 is taken as soon as the level of the mixture increases to the out let valve (time step of 10 minutes). After passing the 600 cm^3 from the tube (equivalent to four pore volume), the sampling would need to stop. The highest allowed pressure to minimize the safety problems is 28 MPa.
7. Step 6 shows the quantity of the deposited asphaltene.

To calculate the pore volume or permeability versus time, it is demanded to use Darcy's law to treat measured data from step 6. The permeability dependence on different parameters can be investigated by following this approach which can determine the level of the damage which is resulted from asphaltene deposition. It is possible to calculate the time dependent concentration of the asphaltene in the final product using data from the latest step (step 7). The operational conditions for the experiments are listed in tables 2 and 3.

Table 2. Input parameters (test conditions) [1, 21, 22]

Parameters	Test #1	Test #2	Test #3	Test #4	Test #5	Test #6
Flow rate, (cm^3/hr)	60	30	30	60	90	30
Concentration of n-C_7 in the mixture, (%)	40	40	60	50	40	50
Concentration of asphaltene in the mixture, (vol./vol.)	0.001811	0.001811	0.003066	0.002462	0.001811	0.002462
Mixture density, (g/cm^3)	0.808	0.808	0.77	0.79	0.808	0.79
Asphaltene density, (g/cm^3)	1.1	1.1	1.1	1.1	1.1	1.1
Mixture viscosity, (cP)	1.1	1.1	0.59	0.71	1.1	0.71
Total length of porous medium, (cm)	1828.8	1828.8	1828.8	1828.8	1828.8	1828.8
Cross-section area of porous medium, (cm^2)	0.30	0.30	0.30	0.30	0.30	0.30
Temperature, (°C)	90	90	90	90	90	90

Table 3. Selected Oil and asphaltene properties [1, 21, 22]

Property	Value	Property	Value
Flow Rate	60 cm^3/hr	Asphaltene concentration, (vol/vol)	0.0024
Viscosity	0.79 cP	Oil density	0.79 g/cm^3
Temperature	90°C		

3. Methodology

3.1. Network and pore geometry

Representation of the porous medium includes a lattice of throats and pores which is arranged rectangularly as the solid blocks are connected to a layer of pores. Circular shape in the cross sectional view are indications of throats and pores. Each pore includes different branches showing the connected throats and their extensive effect on the network. Weibull [19] showed that the distribution of the pore radius lays within a random interval and which be calculated using the following equation:

$$R_r = (R_{t\max} - R_{t\min}) \times \left[-\alpha \ln\left(z\left(1 - e^{\frac{-1}{\alpha}}\right) + e^{\frac{-1}{\alpha}} \right) \right]^{\beta} + R_{t\min} \quad (1)$$

where R_t and z denote throat radius and a positive random number smaller than unity, respectively. Other parameters (α and β) are the statistical constant. The pore radius should not be smaller than largest radius of the throats which can be calculated as follows:

$$R_p = \max\{R_{ti} \mid i = 1,...,n\} \times f \quad (2)$$

where n and *f* (*f* ≥1) denote the throat number and aspect ratio, respectively. The aspect ratio shows the pore radius ratio to the largest throat radius. The topological shape of the lattice is considered to be rectangular which gives a freedom to the throat and pore length to vary. In equation 2, if we replace the l parameter with R, it can change its application from the calculation of pore to the throat length. The network model randomness cab is quantified using equation 1 which defines the index of heterogeneity. Obviously, as the heterogeneity of the system increases, the system would become more heterogenic with a larger index.

$$H_i = \frac{\bar{R} \times \beta \times (f_{max} - f_{min})}{R_{max} - R_{min}} \quad (3)$$

where $\bar{R}$ denotes the average throat/pore radius.

3.2. Passing the fluid from network

Flowing fluid fills the whole cross-section of the element. The resistance of the fluid hydraulic (ω) has a general form which can be calculated as follow:

$$\omega = \mu_f \int_{x_1}^{x_2} \frac{dx}{g(x)} \quad (4)$$

where *g(x)* and μ_f denote conductance fluid per length and viscosity of the fluid, respectively. Poiseuille's law shows the calculation if *g(x)* is considered for a cylindrical flow:

$$g = \frac{\pi}{8} R^4 \quad (5)$$

3.3. Distribution of fluid pressure

In the equation of volume conversion, hydraulic resistance (equivalent) is taken into account. Using this concept, the flow rate of the oil between neighboring throat and pore centers can be calculated by the equation 6:

$$q = \frac{P_p - P_t}{\omega_e} \quad (6)$$

where, indices of p and t are denoting pore and throat, respectively. ω_e denotes hydraulic resistance (hydraulic). A network with a number of throats and b number of pores is considered then conservation of volume for throats and pores is applied.

The conservation of volume is included with equation 6 (equation of flow). This leads to a list of equation systems with a + b unknowns (pressure at pore/throat center) that are illustrated in the Equation 7 and 8 for pores and throats respectively:

$$\sum_{i=1}^{n} q_{ij} = \sum_{i=1}^{n} \frac{P_p^j - P_t^i}{\omega_e^{ij}} = 0 \quad (7)$$

$$\frac{P_p^2 - P_t^i}{\omega_e^{i1}} + \frac{P_p^2 - P_t^i}{\omega_e^{i2}} = 0 \quad (8)$$

where indices j and i indicate throats and pores respectively. 1 and 2 show two connected pores to a throat.

According to Equations 7 and 8 for any network with a + b members (throat/pore), a system of linear equations with a+b unknowns is obtained. Solving the mentioned system including proper boundary condition determines pressure distribution for the network. Network absolute permeability can be calculated based on Darcy's low for single-phase flow; it is assumed that fluid viscosity does not change due to asphaltene precipitation during the process. Having pressure distribution through the network gives the ability to calculate the thermodynamic state of the fluid as well as probability and quantity of deposited asphaltene with respect to the introduced scale in the next section.

3.4. Asphaltene precipitation model

Because of the complexity of the thermodynamics model with a required number of fitted parameters from experimental data, the available parameters are lacking the power to extend the predictions to some unmeasured operational conditions [20]. Therefore, the scale equation is included to predict the asphaltene deposition conditions of the investigated sample [20]. The model includes different parameters such as the pressure of the oil, initial content of the asphaltene inside the oil, bubble point, temperature, pressure and eventually the critical

properties. Properties of the tested asphaltene and oil are provided in Tables 2 and 3. This scaling equation was coupled with previously described network model to predict the amount of deposited asphaltene in each pore or throat.

3.5. Simulation of the precipitation process

Asphaltene deposition is highly dependent on pressure fluctuation of the pore as it is the driving force for flowing the oil in between throat and pore. Changing the condition during this fluctuations would possibly initiate the deposition (basic assumption for scaling rule). Time dependent asphaltene content of the pore and throat can be calculated by equation 8 and following material balance:

$$V_{a,prec} = \frac{\rho_o x v_a}{MW} x f_{a,SE} x V_{p/t} \quad (9)$$

where $V_{a,prec}$, ρ_o, v_a, Mw_a, $f_{a,SE}$ and $V_{p/t}$ denote the deposited asphaltene volume, oil density, molar volume of the asphaltene sample, molecular weight, mass based fraction of the deposit and volume of the throat/pore, respectively.

At each time step the change in radius of each pore or throat is computed according to the following equation:

$$dR_i = \frac{V_{a,prec}^i}{2\pi R_i L_i} \quad (10)$$

where dR_i is a reduction in radius of element i due to asphaltene precipitation, $V_{a,prec}^i$ is the volume of deposited asphaltene in element i, R_i is the radius of element i and L_i is its length.

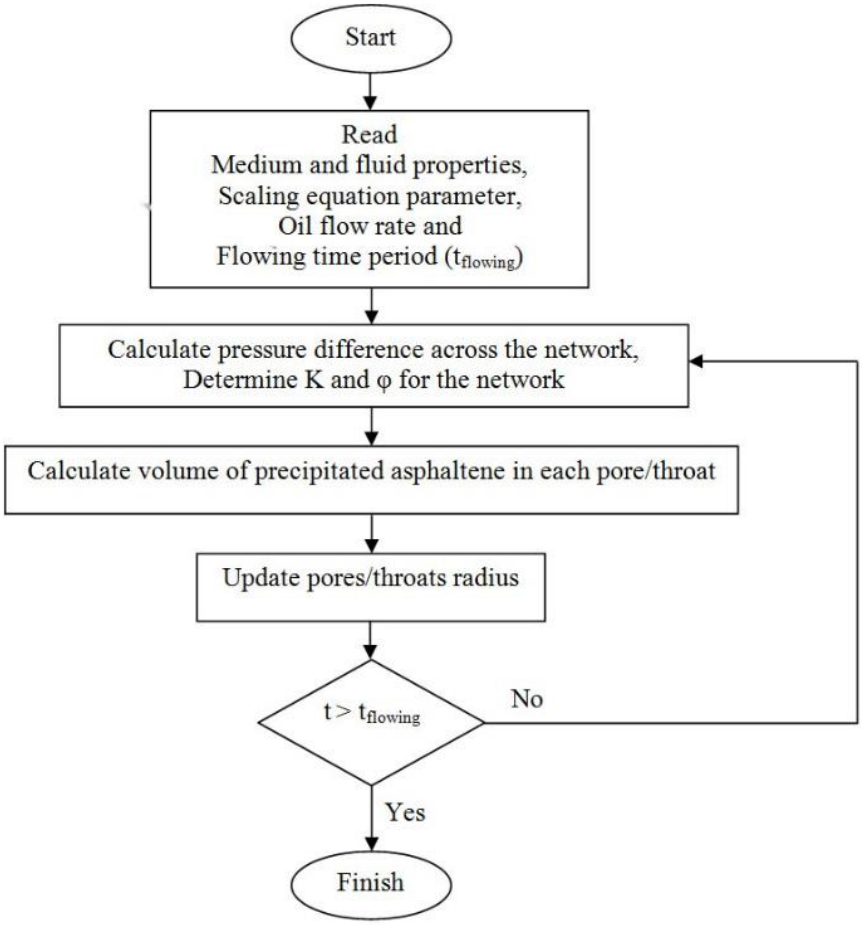

Figure 5. Algorithm for simulation of asphaltene precipitation in network model

The flow chart of the developed computer program is provided in figure 5, which simplifies the discussed mathematical computations. This program was used to simulate the asphaltene precipitation phenomenon in porous medium duo to fluid (asphaltenic crude oil) flow. The network model used this simulation shows only a very small part of the tube; hence, we can neglect the effect of temperature change and assume the process to be in an isothermal condition. To have the similar opportunity of precipitation in both slim tube and network model it is assumed that the network model is entrance part of slim tube consequently a number of filling of the network model with oil is calculated according to the slim tube and network model dimensions and their average porosity:

$$N_f = \frac{V_{BS}\varphi_S}{V_{BN}\varphi_N} \quad (11)$$

where N_f is a number of completely filling of the network model with oil, V_{BS} and V_{BN} are the bulk volume of the slim tube and network respectively, in addition, φ_S and φ_N are porosity of average porosity of slim tube and network, respectively.

3.6. The sensitivity of the network permeability

The morphology defining parameters for the network model are as follows (from the most important to the least important). Distribution of the diameter of pore/throat, length of the throat (pore), an average of the pore coordination number and pore number (throat). At a different range of the length, radius, and number of pores, a one-phase flow is simulated with a network model. Looking at results, one can conclude that the permeability within the range of 10-700 pores is unstable. In the constant condition for the rest of the parameters, results have shown that after 700 number of pores, the system becomes stable and it is less sensitive to the parameter which is shown in figure 6. Hence, the included lattice is made of 24×32 dimensions of pores, which rectifies the limitation.

4. Permeability and porosity reduction due to asphaltene precipitation

In this study, asphaltene precipitation was simulated during oil flow using the pore scale network model with the rate of 60 cc/hr. The oil asphaltene content was 0.0024 (volume/volume) based on the experiment that was performed on the slim tube. Permeability was less sensitive to the change of porosity in comparison with precipitation. The asphaltene precipitation decreases path connectivity for fluid flow. However the deposit volume occupies a small part of the medium, and it doesn't decrease the porosity significantly. This fact is in a good agreement with results of experiment (see Figure 7 and 8). Figures 4 and 5 show normalized permeability and normalized porosity with respect to their initial values for both model and experiment. Some parameters of network model were changed to reach the best match between the network model prediction and experiment results. These parameters values are shown in Table 4. According to Figures 6 and 4, network model could predict porosity reduction more reliably than the estimation of permeability reduction. It might be the result of different heterogeneities of the slim tube and network model. The flow was simulated using three different indices of heterogeneity (H_i) inside the network.

Table 4. Network parameters used in the simulations

Parameter	Value	Parameter	Value
R_{tmin}-R_{tmax}	3-20 μm	A	0.8
l_{min}-l_{max}	10-100 μm	B	1.6
f_{min} -f_{max}	2-2.2		

The more the heterogeneity, the higher the probability to deposit asphaltene (shown in Figure 9). For the presented results *f* and β were varying in equation 3 and the size of the throat radius was constant. As the number of the parameters rises, consequently the complexity of the model increases. Therefore in such simulations permeability alteration is a sensitive function of associated pore volume parameters like pore size distribution and

coordination number. During the described process, pore size distribution changes as a result of decreasing pore/throat radius due to asphaltene precipitation (see Figure 10).

5. Results and discussion

In this study, a pore scale network simulator was used to calculate the change of the porosity and permeability of a 2D porous medium (hypothetical) resulting from asphaltene precipitation. The result were compared to the results of an experiment that was carried out on the slim tube. Initially based on the simplified Navier-Stokes equation pressure distribution through the network is calculated. Thereafter, to predict the fraction of precipitated asphaltene of every pore or throat, a scaling equation is employed with respect to the pressure fluctuations. Finally, distribution of the pore size, porosity, element size reduction and permeability is determined consequently by a material balance for each throat or pore. The pore scale network model predicts the porosity reduction more acceptable than permeability changes. This fact is the result of medium heterogeneity. In fact, the slim tube that was used in the experiments is more heterogeneous than the network model of this study. Simulations show more heterogeneous networks are more sensitive to asphaltene precipitation. Authors recommend that a thermodynamic model which includes the colloidal nature of asphaltene particle is used in such simulation. It should be mentioned that coupling network model with a thermodynamic model is more complex than the model used in this study.

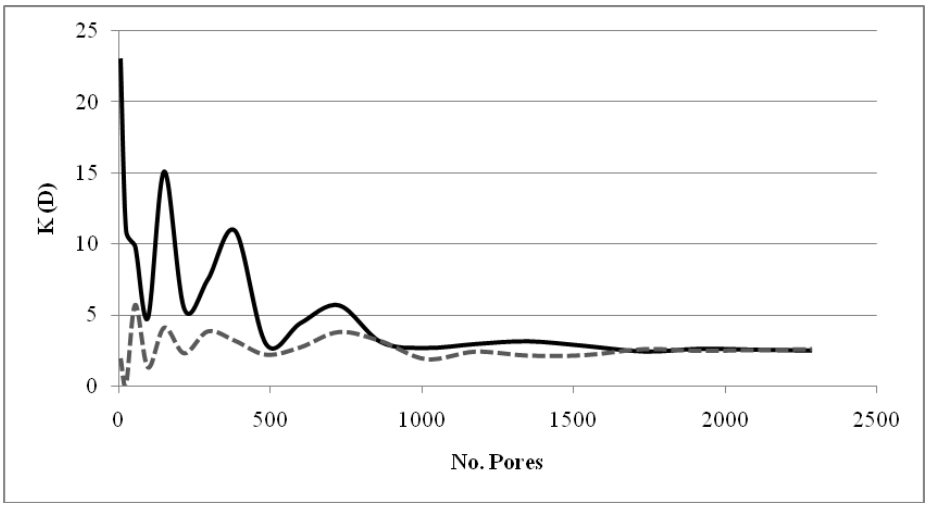

Figure 6. Effect of number of pores on absolute permeability.

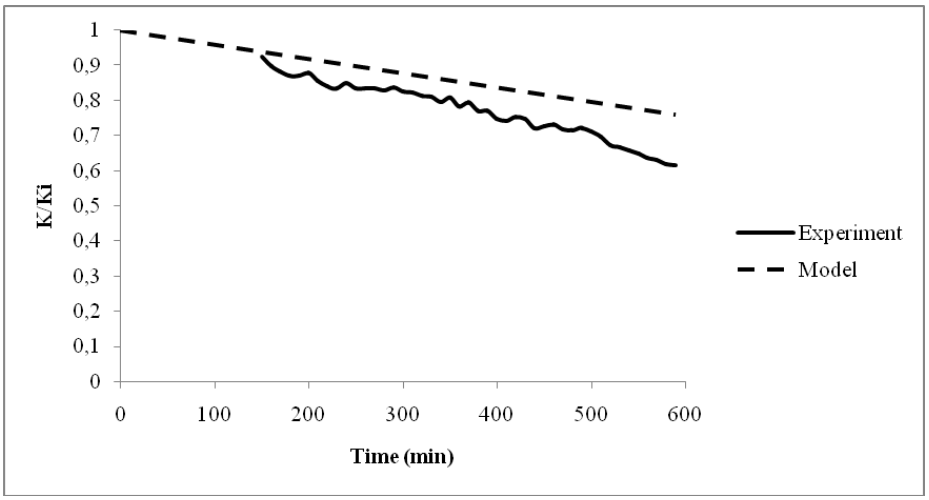

Figure 7. Permeability reduction due to asphaltene precipitation.

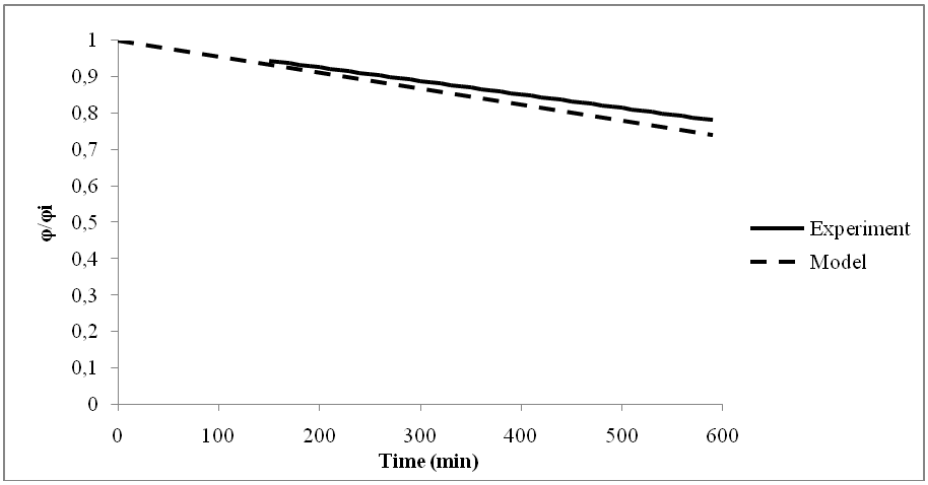

Figure 8. Porosity reduction due to asphaltene precipitation.

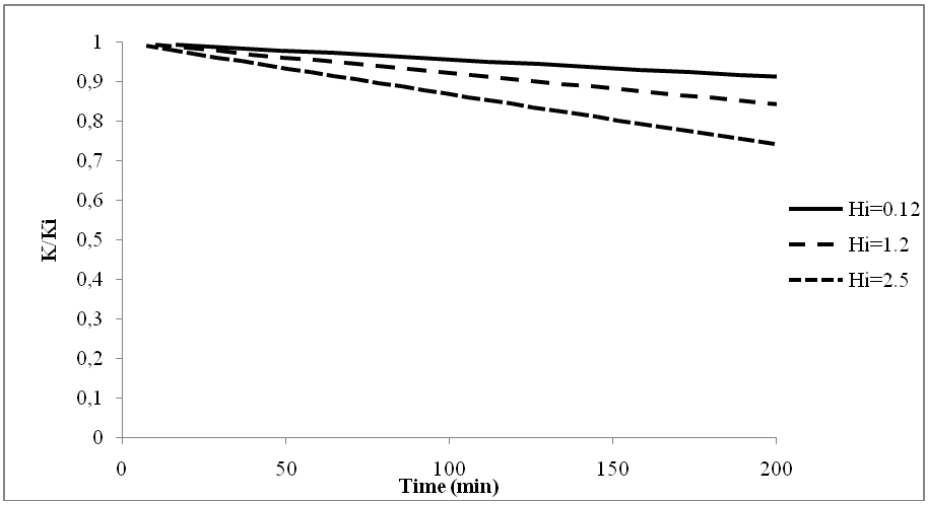

Figure 9. Effect of heterogeneity on permeability reduction.

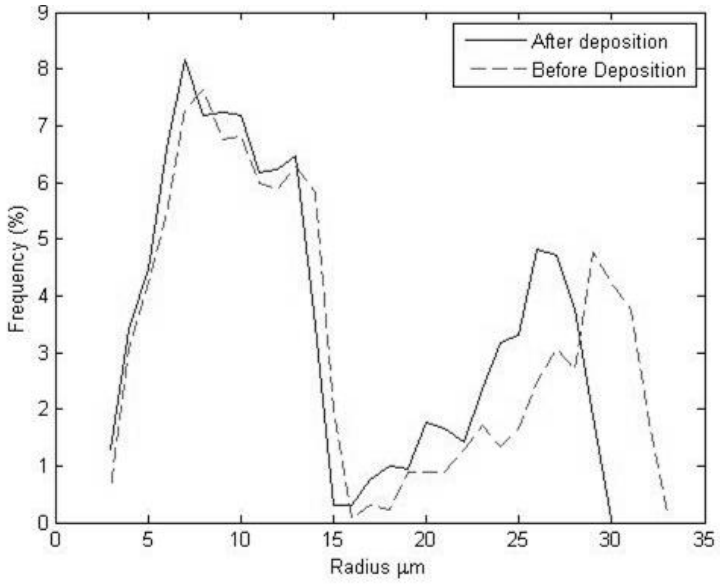

Figure 10. Pore size distribution change due to asphaltene precipitation.

6. Conclusions

In this work, asphaltene precipitation in granular porous media was simulated in pore scale using a network modeling method. The numerical results of pore-scale network modeling for the permeability reduction versus time were developed for the evolution of the permeability of a slim tube during precipitation of asphaltene. The main outcomes of this study can be expressed as below.

- ✓ For enough long slim tubes, the model can be simplified to the form which fits well with the laboratory experiments. The proposed models describe the permeability change with no need to know the changes of porosity.
- ✓ The developed model was coded on the computer. The developed model can simulate the porous medium under the experimental condition to investigate decreasing the permeability. It shows a good correlative agreement with experimental data which indicates the quality of the model.
- ✓ In addition, the change in the distribution of pore size resulting from asphaltene deposition can be calculated.

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To whom correspondence should be addressed: Prof. Amir H Mohammadi, Discipline of Chemical Engineering, School of Engineering, University of KwaZulu-Natal, Howard College Campus, Durban 4041, South Africa, E-mail: amir_h_mohammadi@yahoo.com and Dr. Abbas Khaksar Manshad, Department of Petroleum Engineering, Abadan Faculty of Petroleum Engineering, Petroleum University of Technology (PUT), Abadan, Iran, khaksar@pur.ac.ir