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PREDICTION OF WAX DEPOSITION IN PIPELINE BY CFD TECHNIQUES

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ABSTRACT

Waxy crude oil contains high molecular weight paraffin, which is mostly in the range from C_{15}-C_{75}. When the inner pipe wall temperature is below the cloud point of crude oil, paraffin component is suspended in flow and start to form an incipient gel at the cold surface. This phenomenon can lead to a serious operational problem. The solubility of paraffin molecules is highly dependent on the fluid temperature, therefore, when radial temperature gradient occurs in the pipe, a radial concentration gradient will also develop. This concentration gradient is the driving force for the dissolved paraffin molecules to be transported towards the pipe wall where the dissolved wax concentration is lower. In this paper we consider deposition of waxy crude oil in laminar flow regime. An enthalpy-porosity technique is used for modelling the solidification process. The gel region is treated as a porous zone with porosity equal to the liquid fraction. The solution of the coupled momentum, energy and species balance equations of wax components for each specific level is solved through a finite volume method (CFD); also the pressure-velocity have been calculated through SIMPLE algorithm. We use both molecular diffusion (density gradient is driving force) and thermal diffusion (temperature gradient is driving force) in diffusion flux expression. In our calculations, we consider 2D-axisymmetric pipe geometry. The rate of change for deposition thickness is considered by time and position. The result compared with prediction data is agreeable.

Key words: waxy crude oil, cfd, deposition

NOMENCLATURE

A	mushy factor
C_p	specific heat at constant pressure
D^M	molecular diffusion coefficient
D^T	thermal diffusion coefficient
D^P	pressure diffusion coefficient
I	tensor
h_{ref}	reference enthalpy
Mw	molecular weight
S	source term
T_{ref}	reference temperature
τ	extra shear tension
ρ	density
V	volume
β	liquid fraction
$\vec{v}$	velocity of fluid
r	radial distance from pipe center
x	mole fraction

INTRODUCTION

The crude oil being exploited out of the great depth under the ground includes heavy hydrocarbons and semi-heavy hydrocarbons with different forms and characteristics. Heavy hydrocarbons include waxes, asphalt materials and resins, which are found as solid. Waxes are usually composed of linear parraffin with carbon numbers ranging from 15 to 75. In the flow of crude oil in the pipeline, when the temperature in the inner layer of the pipe is less than cloud point temperature, wax depositions begin to form a gel-like layer on the cold surface of the pipe (Chin, 2001). In turn, these depositions cause of underground pores, decrease their penetrability and as a result they decrease the output of oil extraction.

The deposition formation will also cause numerous problems throughout the procedure. For instance, it may clog pipes, increase resistance against the flow and as a result pressure decrease over the pipe. Furthermore, instrument should work with higher power and this untimely wear and tear.

The deposition caused by crude oil containing wax is a complicated issue modeled by different theories. The deposition includes solid and liquid phases in the gel whose structure and relative coordinates varies in the width of deposition concentration with temprature variation and shear stress. Berger et al 1981, considered four mechanisms for wax deposition: molecular diffusion, shear dispersion, brownian diffusion, gravity settling (Mehrotra and Bhat, 2006). Hamouda & Ravnoy 1992, describe molecular diffiusion as the most important mechanism. Brown et al 1993, presented a practical method for calculating wax deposition rate on the inner surface of the pipe based on molecular diffiusion. Rigg et al 1998, simulated a model based on a similar model. Fogler et al 2002 & 2003, studied the inner –diffiusion of gelly wax deposition; besides they studied of wax deposition on the pipe wall, they also consider reciprocal diffiusion of oil molecules outside the wax depositon. Fogler`s model, models various condition observed in wax deposition, but it needs differential calculus. Hernandez 2002, described a similar sample in which the deposition

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is modeled by mass transfer or by a emperical expression for oil molecules transition to outside of gel (Szczepaneski and Zhang, 2007). Mehrotra et al 2005 introduced a mathematical model based on moving boundary theory for deposition growth from paraffin mixture regarding the heat transfer in the pipe. Unlike the previous researcher, they assumed that heat tranfer effects are among the sinificant agents for wax deposition (Firoozabadi, Banki and Hoteit, 2008). Hoteit, Firoozabadi and banki in their recent studied presented a mathematical model for prediction of wax deposition in laminar flow.They used numerical method of enthalpy-porosity for solved their suggestion equations. In this method the wax-gel area of oil considered as a porous material(Zumaeta, Byrne ND Fitzpatrick, 2007).

Nowadays, application of numerical method in computer calculations is of great importance and they are used in designing engineering tools. The science of computational fluid dynamics(CFD) has turn into a strong tool available to researchers and engineers for analyzing the behavior of fluid flow and heat transfer in systems with unbalanced geometry and complicated equations. It has made a significant improvement through the last two decades. Colpatzic 1998, applied CFD for 3D modeling of natural gas flow in pipeline prediction of temperature. They showd CFD is a usefull means for quantitative analysis of non-isothermal flow in complicated 3D geometry. In 1999, Tanner used a cylindrical system of limited volume formulation in order to simulate problems in viscoelastic flow. Evans 2000, through an article proved that many of CFD codes employed in pipelines in their solved from meshing structure uses one-dimentional seperated partes, while for a better scale parts with two or more dimentions should be employed. Accordingly, they came up with an algoritm for multi-dimentional meshing by fortran encoding system. Lee & Web 2004, conduted an experiment to study and calculate solid particle deposition in horizontal pipeline in air transfer system. In their calculations, they used DEM method for solid particle and CFD method for constant-gas mode. Zoomta 2006, showed by CFD simulation that breaking deposition particle along turbulant flows inside the pipeline happens in the beginning of the pipeline as well (Easa and Barigo, 2007). In this article CFD is applied to describe the crude oil flow in the pipeline.

In this paper, the oil fluid flow in the pipeline is modeled by 2D-axisymmetric geometry. The fluid is considered binary. The fluid flows laminar and in-compressible. Given the fact that the temperature has significant effects on wax deposits on the cold surface of the pipe, this paper has used temperature in the model and model is describe in non-isothermal conditions. The transient deposition of each component is calculated from the solution of the coupled Continuity, momentum and energy equations at the local level. One of the major setbacks in the phase change studying is that a moving boundary surface separates two phases with different physical characteristics. There are numerical models for studying phase change investigation including enthalpy-porosity approach. This theory is applied based on the fixed-grid model for calculating physical details of phase change. In this paper, wax depopsition and solidification process are studied through enthalpy-prosity approach. In this theory we have considered the deposit layer as a pseudo-porous material. Many are the researchers who have studied the crystal structure of the wax. The wax concerts to gel due to the clotting of wax crystal in the solution. In microscopic observations, its structure forms netlike overlapping surfaces describe the level of reduction of velocity in gel because of solid formation, Darcy source clause is added to the momentum equation. Two signtificant processes influence wax deposition in the flow: 1) heat transfer and 2) particle flux. Heat transfer is done through conduction. Particle flux influences wax deposition through diffiusion into it. In this one we use both of molecular diffusion and thermal diffusion in species transfer. Crude oil and wax-sedimentation is processed by means of FLUENT software. The observed wax deposition thickness and temperature along the pipeline were compared with the obtained results by Firoozabadi(Firoozabadi, Banki and Hoteit, 2008).

APPLICATION OF CFD IN PIPELINE

CFD includes the analysis of fluid flow system, heat transfer and accompained phenomena like chemical reaction based on computer simulation. CFD is a very efficient way such that it includes a wide range of industrial and non-industrial applications. The structure of a CFD program is numerical and problemes related to fluid flow are solved by this. Theses program consist of three major parts: processor, solver and post-processor. Generally speaking, solving a problem follows the number of cells in the network. Conseguently, the more number of cells have a better accurate. To establish CFD model for pipeline the following 6 steps are to be taken.

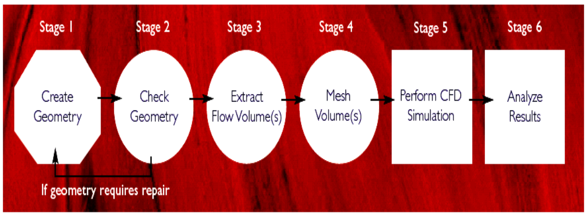


Figure 1. the CFD simulation pipeline

As illustrated in figure 1, the process begins with establishing the total of one or more geometric structure. To avoid future difficulties, it is important to check the geometry. The next step is to calculate flow valume since our calculation is a two dimentional one. To modify the geometric charactristics, we meshing the structure. The prepared structure is simulated in this phase and following this the result are studied by means of FLUENT (Versteeg, 1960).

GOVERING EQUATION

- Momentum equeation

In stating the momentum equation, all forces at work on the flow should be taken into consideration.

$$\frac{\partial \rho \underline{\upsilon}}{\partial t} = -\nabla .(\rho \underline{\upsilon}.\underline{\upsilon}) - \nabla .\underline{\underline{\Pi}} + \rho g \qquad (1)$$

The stated sentences in the above equation are from left to right. momentum reduction rate in constant volume(V), the rate of output momentum flux by transfer, the net molecular force applied on fixed volume (V) and body force on volume V.By seting $\underline{\underline{\Pi}} = P\underline{\underline{I}} + \underline{\underline{\tau}}$, using the continuity equation, momentum equation will be [9]:

$$\rho(\frac{\partial \upsilon}{\partial t}+\underline{\upsilon}.\nabla\underline{\upsilon})=-\nabla P-\nabla.\underline{\underline{\tau}}+\rho\underline{\underline{g}}+S \quad (2)$$

At the time solidification there will be a moveing boundray between solid-liquid. The most important issue is calculation of velocity deceleration in gel layer with fixed-grid net work. Voller et al. 1998 have introduced an enthalpy–porosity approach to simulate freezing of liquids thermal cavity. In this theory, we consider phase change in a porosity material with porosity β . The porosity reduced from 1 to 0 as a solid fraction increase from 1 to 0. To describe velocity deceleration, darcy source (S) is added to momentum equation as stated below:

$$S=\frac{(1-\beta)^2}{(\beta^2+q)}A_{mush}\vec{v} \quad (3)$$

The value of A mushy depends on the morphology of porous media. For the wax morphology, regarding the refrence $A_{mush}=10^6\ m^{-2}$. β is the value of liquid fraction in each cell which ranges between 0 to 1. q is a little value (0.001) to avoid the value of fraction from turning to 0.

- Energy equation

$$\frac{\partial}{\partial t}(\rho H)+\nabla.(\rho\vec{v}H)=\nabla.(k\nabla T)+S \quad (4)$$

H is enthalpy, which defined by following equation[9]:

$$H=h+\Delta H \quad (5)$$

$$h=h_{ref}+\int_{Tref}^{T}C_P dT \quad (6)$$

The latent heat content can now be written in terms of the latent heat of the material, L:

$$\Delta H=\beta L \quad (7)$$

The latent heat content can vary between zero (for a solid) and L (for a liquid).

In the case of multicomponent solidification with species segregation; solidification with species transport, the solidus and liquidus temperatures are computed from these equations:

$$T_{solidus}=T_{melt}+\sum_{solutes}K_i m_i Y_i \quad (8)$$

$$T_{liqudus}=T_{melt}+\sum_{solutes}m_i Y_i \quad (9)$$

where Ki is the partition coefficient of solute i, which is the ratio of the concentration in solid to that in liquid at the interface, Yi is the mass fraction of solute i, and mi is the slope of the liquidus surface with respect to Yi.

The liquid fraction β can be defined as:

$$T<T_{solidus} \quad \Rightarrow \quad \beta=0$$

$$T>T_{liqudus} \quad \Rightarrow \quad \beta=1$$

$$T_{solidus}<T<T_{liqudus} \quad \Rightarrow \quad \beta=\frac{T-T_{solid}}{T_{liq}-T_{solid}} \quad (10)$$

- Species transport equation

In solidification by species transport equation is (morrison, 2000):

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla.(\rho\left[\beta\vec{v}_{liq}Y_{i,liq}+(1-\beta)\vec{v}_P Y_{i,sol}\right]+-\nabla.j_i+R_i \quad (11)$$

Where J_i is molecular diffusion flux and R_i is rate of reaction. Molecular diffusion flux in a vector form be written:

$$J=-c(D^M\nabla x+D^T\nabla T+D^P\nabla P) \quad (12)$$

$D^M\nabla x$ is molecular diffusion, $D^T\nabla T$ is thermal diffusion and $D^P\nabla P$ is pressure diffusion.

Parrafin molecular solubility depends on the fluid temperature. Thus, in case of temperature differences occur along the pipe redius, there will be concenteration differences as well which in turn causes a driving forces that pushes the solved wax molecules toward the surface of the pipe where concentration is lower. Fick`s rule to describe the rate mass transfer regarding the molecular diffiusion is defined as follows:

$$J=-\rho D^M\frac{\partial x}{\partial r}=-CD^M\frac{\partial x}{\partial T}\frac{\partial T}{\partial r} \quad (13)$$

Fick’s law was developed for isothermal, and uses in processes where only the diffusion due to a concentration gradient is considered; neglecting any mass diffusion from temperature gradient, pressure gradient or external forces. Study the reason of deposition needs measuring mass diffusion, regarding temperature gradient. Hence, the appropriate expression for diffusion flux for wax deposition in equation number (9) regardless of pressure diffusion will be:

$$J_i=-C_j(D_j^M\nabla x_j+D_j^T\nabla T) \quad (14)$$

The first term on the right side is known as the Fick’s law and the second term is often referred to as the Soret effect (Firoozabadi, Banki and Hoteit, 2008).

PROBLEM DEFINITION

When the temperature in waxy crude oil reaches below wax formation temprature, gel-like wax layer forms deposition on the cold inner surface of the pipe. As a result of temperature drop and wax diffusion, the gel layer beging to grow. The studied model is for laminar flow, and in this paper shear dispersion and gravity settling and not considered. Due to not regarding gravity settling the three-dimensional geometry of pipe is reduced to two-dimensional. The pipe radius equals 0.001841 m, length 0.25 m and thichness 0.0013 m. regarding the reference data (Firoozabadi, Banki and Hoteit, 2008) fluid is the mixture of light oil species (*n*-octane) and a heavy cycloalkane (nonadecylcyclohexane; cycloC6C19). The flow is a function of time with the flow rate of 63 ml/min and Reynolds number is 526. The input flow temperature is $25\,^\circ C$ and the surface temperatute is $0\ ^\circ C$. Mole fraction of cycloalkane is 0.08. Some of the other properties of material are in the table (1).

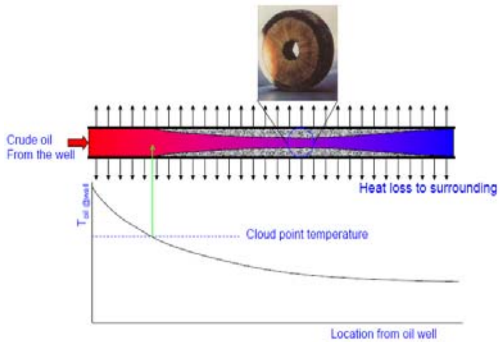


Figure 2. Wax deposition occurs when the inner wall temperature is below the cloud point temperature.

Table 1. Properties of oil fluid (Firoozabadi, Banki and Hoteit, 2008)

Glass(wall)	$cycloC_6C_{19}$	nC_8	properties
$2230\,\frac{kg}{m^3}$	$827\,\frac{kg}{m^3}$	$699\,\frac{kg}{m^3}$	density
$17.4\,\frac{w}{m-k}$	$0.19\,\frac{w}{m-k}$	$0.13\,\frac{w}{m-k}$	Heat conductive coefficient

Melting temperature of crude oil due to Won theory is:

$$T_i^f = 374.5 - 0.02617Mw_i - \frac{20172}{Mw_i} \qquad (15)$$

Won developed a correlation for calculating the enthalpy of fusion of paraffin hydrocarbons:

$$\Delta h_i^f = 0.1426 \times Mw \times T_i^f \qquad (16)$$

Where enthalpy is in $cal/gmol$ and T is in K (Dalirsefat and feyzi, 2006).

GRIDDING

Here, we have modelled the horizontal pipe in the two-dimensional axisymmetric computational domain and in form of a cylinder (R, X). Since the gradient near the surface are high, while the velocity gradient near the centre are low. Meshing in case of (R_r, R_x) are respectively equal to 29×30. Gridding is done by means of GAMBIT software. Figure (3)

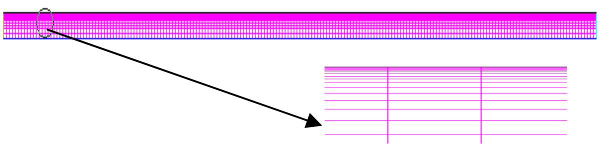
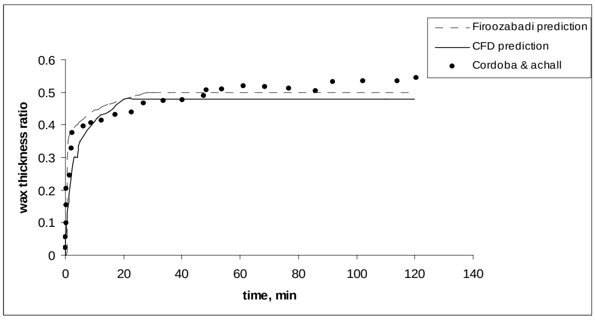


Figure 3. Meshing of pipe by GAMBIT

RESULT

With place boundary condition and solve the related equation, we obtain these result: Figure (4) presented of the deposition thickness ratio vs. time at flow rate of 63 ml/min. The result is compared by result of Firoozabadi & Data from Cordoba & Schall. Our prediction and result of have a good agreement. Cordoba & Schall measured the wax deposition thickness in the flow loop system. They evaluated the amount of deposition by use of two method of 1) heat transfer method 2) Gravimetric method. They concluded that heat transfer method have the less error. We compared our prediction by heat transfer method. In Firoozabadi prediction, they used multisolid-phase model by Lira-Galeana to perform the solid-liquid phase calculation (Firoozabadi, Banki and Hoteit, 2008). The figure shows that by passing of time, rate of deposition thickness increasing. During the first few time the gel formation on the wall is very rapid and growth of wax deposition stop after a certain period of time. This condition arises as a result of the insulating effect of the thermal resistance of wax deposit.



Figure(4)- deposit thickness ratio vs. time

In figure (5) we see temperature differences at the pipe midsection vs. radial distance at the time (t= 1 minute). We compared our prediction by result of Firoozabadi (Firoozabadi, Banki and Hoteit, 2008). Whatever time increasing, the temperature differences across the radius increasing. Figure (6) shows temperature averaged over the radius along the tube length after 10 minute. The predicted temperature difference between the inlet and outlet is about 0.3 $^\circ C$ .It has a good agreement by Firoozabadi prediction.

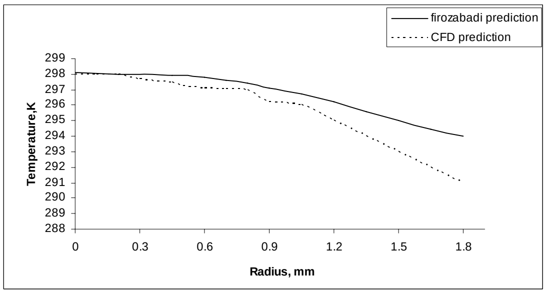


Figure (5) - temperature at the pipe midsection vs. radial distance

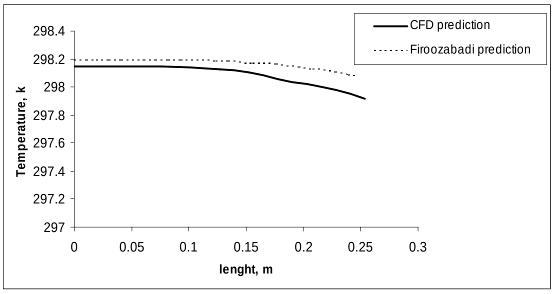


Figure (6) - temperature averaged over the radius vs. axial distance

CONCLUSION

We consider flow of waxy crude oil when cross cold wall in the pipeline. The fluid flowing by single phase until the temperature of fluid reach cloud point of crude oil. In this time paraffin component suspend in flow and form a gel at the cold surface. This deposition occurs during flowing of fluid in pipe and may shut down the pipe and make some problems. By temperature differences in radial gradient we also have concentration gradient. Both of these cause deposition on the cold surface. In this paper we consider laminar flow regime. For modelling solidification we use enthalpy-porosity technique. The solution of the coupled momentum, energy and species balance equations of wax components for each specific level is solved through a finite volume method (CFD). In diffusion flux we use both molecular and thermal diffusion. Rate of deposition thickness increasing by time, and after about 20 minute it reaches constant amount. We show decreasing temperature along radial coordinate, and it has good agreement by prediction data. In this paper we more consider mathematical relative of deposition in pipe. For future we will struggle to review thickness differences in different velocity and turbulence regime.

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