THERMAL EFFECTS ON THE CRUDE OIL FLOW

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ABSTRACT
The aim of our study is based on modeling the flow of non-Newtonian fluids such as crude oil in pipelines. The transport of hydrocarbons in pipelines is often disturbed by several parameters such as thermal effects, the pipeline geometry, the pressure, the viscosity, the density, and the fluid-solid interaction. But, since crude oil is a non-Newtonian fluid, its complex flow cannot be described by conventional models. To treat this, we used the models of Phan Thien and Tanner (PTT) and Maxwell by taking into account the laminar regime. The obtained results converge to the experimental ones.

INTRODUCTION
Pipelines are widely used for transporting fluids in a variety of applications such as water distribution networks, oil pipelines, power plant steam lines. In such cases, the effect of temperature has a great effect on rheology via the viscosity function that is to say heat exchange results in increasing or decreasing viscosity of the fluid due to the reduction or augmentation in fluid temperature. As an example, Denn [1] has shown that for spinning calculations both non-Newtonian isothermal and non-isothermal Newtonian cases can be made to fit the data almost equally well with small adjustments of the surface heat transfer coefficient. Therefore, it is often most important to consider temperature in flow. Furthermore, many studies of the heat transfer associated with phase changes occurring around a pipeline, inside a pipeline, or in porous media have been reported. In this case of heat transfer associated with phase changes occurring in the region around a pipeline, solidification studies around a single cylinder have been conducted by Bathelt and Viskanta [2] and Cheng et al. [3]. Mathematical modeling of the thermal interactions between a pipeline carrying oil or gas and frozen soil under steady-state and non steady-state conditions has also been described by Bronfenbrener [4], Furman [5].

In many cases reported by Bronfenbrener and Korin [6], the approximate quasi-steady approach can provide a fast and simple solution, with acceptable accuracy for practical engineering purposes. Bronfenbrener and Korin [6] proposed an approximate two-dimensional theoretical model based on a quasi-steady approach for thermal analysis of phase change processes around an insulated pipeline buried horizontally in semi-infinite frozen soil. The model was verified by comparison with numerical and other approximate solutions in the literature. The theoretical results show that the propagation of the thawing/freezing interface is limited under constant boundary conditions. The reverse process occurring as a result of interruption of the fluid flow was also examined. Based on the solution for prediction of the boundary location of the thawing region, an analytical equation for determination of the fluid temperature as a function of time was developed. This paper studies the great importance of non-Newtonian fluid property changes with temperature.
of crude oil in pipelines, which is the most important part of the process simulation. The rheological models used for this study are PTT and Maxwell models by varying the following parameters: consistency coefficient, power law exponent, relaxation time. The obtained numerical results, which are in good agreement with the experimental ones (Barry [7]), show that the shear stresses of the flow (so the viscosity of the fluid) decrease with the rise of temperature for both PTT and Maxwell models.

MATHEMATICAL FORMULATION

Heat transfer model: The basic mechanisms of heat transfer by conduction, convection and radiation are generally thought to be independent of whether or not the material is Newtonian or non-Newtonian and this will be assumed in what follows, for thermally isotropic materials:

\[ q_i = -k \frac{\partial T}{\partial x_i} \]  \hspace{1cm} (1)

Where \( q_i \) is the heat flux vector and \( k \) the thermal conductivity, which may be a function of temperature.

In convection, the heat transfer coefficient \( (h) \) will be used:

\[ q_w = h(T_w - T_f) \]  \hspace{1cm} (2)

Where the flux of heat normal to a bounding surface \( q_w \) which is at a temperature \( T_w \) is given by (2);

\( q_w \) is the flux from surface of fluid (bulk temperature \( T_f \)), the equation (2) amounts to a definition of \( h \), the heat transfer coefficient depends on the properties and flow field and can be defined locally or globally.

In summary, the heat transfer considered here is classical. There are at least theoretically, the possibilities of thermomechanical effects. For example, when we could see that the flow of heat in a material depends on the strain or the flow zone.

Equation of energy: The energy equation is written as follows [8]:

\[ \rho \frac{De}{Dt} = \sigma_{ij} \frac{\partial q_i}{\partial x_j} + \rho s \]  \hspace{1cm} (3)

Where,

- \( q_i \): the heat flux vector.
- \( e \): specific internal energy.
- \( \sigma_{ij} \): stress tensor.
- \( s \): integration surface
- \( \rho \): volumic density.

This energy equation is valid for incompressible and compressible materials.

Flow laws: In this section, we discuss models frequently used to characterize the evolution of viscosity as a function of temperature and shear rate (or pulse in dynamics). The models used are proven and widely assimilated. The flow of polymers is very sensitive to shear. Therefore, the Newtonian law, which considers the viscosity as a function of temperature only, does not be applied. Rheological laws are often structured empirically, but some have the advantage of having a physical sense and use the basic parameters of the material [8].

Power law: The power law relates the viscosity to a power rate of shear involving a parameter that depends only on the temperature [8].

\[ \eta_m(\dot{\gamma}, T) = \eta_0(T)\dot{\gamma}^{n-1} \]  \hspace{1cm} (4)

This law allows to decouple the effect of temperature and shear. The index \( n \) is called flow index or index of pseudoplasticity. It is unitless and is characteristic of the material. So our equation becomes as follows:

\[ \eta_m = k\dot{\gamma}^{n-1} \exp(-\alpha(T - T_0)) \]  \hspace{1cm} (5)

Time-temperature shifting: Here, we only looked at the quantity \( a_T \) as a device for correlating the viscosity of the polymer with a zero shear rate. However, there is a lot of significance because it
also gives a scale of time-temperature shifting [8]. Considering a material undergoing a relaxation stress. The relaxation rate is determined by an internal time scale in material. As the temperature rises, and the quantity of molecular motion that occurs in a unit of observer’s time, the timescale shortens so that the relaxation proceeds rapidly. Suppose that changes in time scale so that unit of time is now equivalent to units of \( a_T \) of the observer time, \( a_T \) is a decreasing function of temperature \( T \). Let \( G_t (t, T) \) the relaxation stress modulus at a constant temperature \( T \), and \( G(t) = G(t, T_0) \) reference modulus at a temperature \( T_0 \). We let \( a(T_0) = 1 \), and then assume

\[
G(t,T) = \left( \frac{\rho T}{\rho_0 T_0} \right) G(t/a(T))
\]

(6)

With

- \( \rho \) density at a temperature \( T \).
- \( \rho_0 \) density at a temperature \( T_0 \).

This represents a scale such that \( G(t, T) \) has the same shape but not the same scale at all temperatures. Now, we made a connection between the viscosity at zero shear rate \( \eta_0(T) \) and \( G \):

\[
\eta_0(T) = \int_0^\infty G(t,T)dt = a(T) \int_0^\infty G(t')dt'
\]

(7)

\[= a(T) \left( \frac{\rho T}{\rho_0 T_0} \right) \eta_0(T_0)\]

So

\[
\log \left( \frac{\eta_0(T)}{\eta_0(T_0)} \right) = \log a(T) + \log \left( \frac{\rho T}{\rho_0 T_0} \right)
\]

(8)

In equation (8), \( \log a(T) \) is always much greater than \( \log (\rho T/\rho_0 T_0) \), and the last factor can usually be ignored. Except for small \( \rho T/\rho_0 T_0 \) factors, equation (8) agrees with the previous definition of \( a_T \). We see that \( a(T) \) is the time shift factor with which we can calculate the average time of relaxation:

\[
\bar{\lambda}(T) \eta_0(T) = \int_0^\infty t G(t,T)dt
\]

(9)

\[
= \eta_0(T_0) \bar{\lambda}(T_0) \left( \frac{\rho T}{\rho_0 T_0} \right) a^2(T)
\]

\[
\bar{\lambda}(T) = \bar{\lambda}(T_0) a(T)
\]

(10)

More generally, the molecular theory, Bird [9] lead us to count as non-Newtonian fluids. The shift factor under the form for polymer solutions is represented as follows [9]:

\[
a(T) = a_T = \frac{\left[ \eta_0 - \eta_s \right] T_0 \rho(T)}{\left[ \eta_0 - \eta_s \right] T_0 \rho(T)}
\]

(11)

Where, \( \eta_s \) is the viscosity of the solvent, and to calculate the viscosity, we used the following formula:

\[
\eta - \eta_s = \lambda n_0 KT
\]

This form can be easily derived from the theory of dilute solution, with

\( \eta \): viscosity
\( \eta_s \): viscosity of the solvent.
\( \lambda \): time constant.
\( n_0 \): number of molecules per unit of volume.
\( K \): Boltzmann constant.
\( T \): absolute temperature.

**NUMERICAL MODELING**

To study the thermal effects of crude oil in pipelines, we are going to implement some rheological models on the flow of crude oil such as:

PTT and Maxwell models
**PTT model:** The equation of non-isothermal PTT model is as follows:

\[
\lambda_0 \frac{\Delta F^{-1} \tau_i}{\Delta t} + \sigma_i(\tau \tau_i) F^{-1} \tau_i = 2 \eta_m a_T d
\]  

(20)

\[
a_T = \frac{\left[ T_0 T_0 \rho(T) \right]}{\left[ T_0 T_0 \rho(T) \right]}
\]

(21)

\[
F^{-1} \tau \approx (\rho T_0 / \rho T)
\]

(22)

To calculate the viscosity, we used the formula for power law as follows:

\[
\eta_m = k \dot{\gamma}^{-n-1} \exp - \alpha(T - T_0)
\]

(23)

And to calculate the density, we have the equation as follows:

\[
\rho(T) = \rho_0 / \left[ 1 + \varepsilon(T - T_0) \right]
\]

(24)

**Projection non-isothermal PTT model:** After the projection of the equation of PTT model along the three axes, one obtains the system of ordinary differential equations as follows:

\[
\begin{align*}
\frac{\partial \tau_{r_n}}{\partial t} &= -\frac{\sigma_n}{\lambda_n d_T} \tau_{r_n} - \frac{\lambda_n}{\lambda_n d_T} \tau_{r_n} - \frac{\lambda_n}{\lambda_n d_T} A \zeta \tau_{r_n} \\
\frac{\partial \tau_{r_2}}{\partial t} &= -\frac{\sigma_2}{\lambda_2 d_T} \tau_{r_2} - \frac{\lambda_2}{\lambda_2 d_T} \tau_{r_2} - \frac{\lambda_2}{\lambda_2 d_T} A \frac{\zeta}{2} \tau_{r_2} + \frac{\zeta}{2} \left( \frac{\zeta}{2} - 1 \right) \tau_{r_2} + \frac{\eta_m(T) \rho T_0}{\lambda_2 \rho_0 d_T} A \\
\frac{\partial \tau_{r_3}}{\partial t} &= -\frac{\sigma_3}{\lambda_3 d_T} \tau_{r_3} - \frac{\lambda_3}{\lambda_3 d_T} \tau_{r_3} - \frac{\lambda_3}{\lambda_3 d_T} A (\xi - 2) \tau_{r_3}
\end{align*}
\]

(25)

**Maxwell model:** The equation of non-isothermal Maxwell model is as follows:

\[
\lambda_0 \frac{\Delta F^{-1} \tau}{\Delta t} + F^{-1} \tau = 2 \eta_m a_T \ D
\]

(26)

Where,

\[
F^{-1} \tau = (\rho_0 T_0 / \rho T)
\]

(27)

And

\[
a_T = \frac{\left[ T_0 T_0 \rho(T) \right]}{\left[ T_0 T_0 \rho(T) \right]}
\]

(28)

To calculate the viscosity, we used the formula for power law as follows:

\[
\eta_m = k \dot{\gamma}^{-n-1} \exp - \alpha(T - T_0)
\]

(29)

And to calculate the density equation is as follows:

\[
\rho(T) = \rho_0 / \left[ 1 + \varepsilon(T - T_0) \right]
\]

(30)

**Results and Discussion:**

Temperature has a strong effect on viscosity and viscous behavior. This effect provides the flow behavior curve in terms of shear stress and temperature.
According to the calculation of developed Matlab programs, the obtained results show a good agreement between the numerical results of Maxwell and PTT models and the experimental ones, by making a parametric study of the following parameters:

- The power law exponent $n$,
- The consistency coefficient $k$
- The relaxation time $\lambda$

Figures 1 to 7 show the effect of temperature on viscosity shear stress for Algerian crude oil over the range of 270-340 K. It is observed that, for $n = 0.75$, $k = 0.01$, $\lambda = 2.7e^{-4}$, PTT and Maxwell rheological fit very well measurements.

The interest of these models is to consider rheological characteristics of crude oil such as the interactions between oil and water, and the non-Newtonian considering the effects of temperature.

Figure 1
Comparison of experimental results and the PTT model for Algerian crude oil with different powers $n$.

Figure 2
Comparison of experimental results and the Maxwell model for Algerian crude oil with different powers $n$.

Figure 3
Comparison of experimental results and the PTT model for Algerian crude oil with different relaxation time $\lambda$. 
Comparison of experimental results and the Maxwell model for Algerian crude oil with different relaxation time $\lambda$.

Shear stress as a function of temperature and time for crude oil (Maxwell model).

Shear stress as a function of temperature and time for crude oil (PTT model).

Shear stress as a function of temperature for the Algerian crude oil (comparison of experimental results with the models of Maxwell and PTT).

CONCLUSION

We tried in this work to emphasize the great importance of fluid property changes with
temperature. It is often the most important part of the process simulation. The combination of variable temperature with viscoelasticity practically dictates that numerical methods are used to study these flows and compare with experiment.

The PTT and Maxwell models have been exploited to reach the goal of our work which was to describe thermal effects on the crude oil flow by giving the role of stresses on the pipeline walls.

**KEYWORDS:**
Crude oil, viscosity, pipeline, shear stress, Non Newtonian, PTT model, Maxwell model.

**REFERENCES**
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