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Numerical study of flow restart in the pipeline filled with weakly compressible waxy crude oil in non-isothermal condition

Lalit Kumar *, Kistofer Paso, Johan Sjöblom

Ugelstad Laboratory, Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), N-7491 Trondheim, Norway

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ABSTRACT

The impact of differential thermal heating on pressure propagation is assessed for pipelines filled with weakly compressible gel. The temperature influence on a strain (shear history) dependent rheological model is established from literature data. In order to consider thermal effects on the pressure propagation and flow restart, temperature of the pipeline wall is assumed to be above the wax appearance temperature. The impact of thermal treatment on pressure propagation is analyzed as heat is conducted axially and radially in the pipeline and degrades the gel rheology. Commensurate with weakly compressible fluid properties, isothermal compressibility and fluid thermal expansion coefficients establish density as a function of pressure and temperature. Comparison of results for non-isothermal and isothermal conditions validates the selected numerical algorithm. Axial conduction is negligible in comparison to radial conduction due to the large pipe aspect ratio. Convective flow penetrates only a small axial distance during the pressure propagation process. It is shown that by providing differential heating of gel, the restart process may be accelerated by several orders of magnitude. Preheating of the gel is thereby shown to be an effective method for increasing the velocity of the pressure wave. Finally, it is also shown that the gel deforms faster in the presence of heating, further facilitating flow commencement.

1. Introduction

Waxy crude oil comprises nearly 20% of the world oil reserves [1,2]. Recent exploitation of unconventional waxy crude reserves provides new flow assurance challenges for the petroleum production industry. Pipeline shut-in is often unavoidable due to emergency situations and maintenance requirements. During shut-in, the fluid temperature drops below the wax appearance temperature (WAT) in cold subsea conditions. Below the wax appearance temperature, paraffins present in the crude oil start crystallizing [3], eventually resulting in formation of an interlocking gel-like structure which modulates the crude oil rheological properties [4–6]. The complex rheology and high effective viscosity of waxy crude oil below the WAT leads to operational challenges. Successfully assuring flow restart in gelled pipelines subsequent to shut-in constitutes a significance hindrance to the production of unconventional waxy crude resources. In the current investigation, the combined effects of inertia, viscous flow and gel breakage upon pressure propagation are investigated under non-isothermal conditions.

Several researchers have investigated pressure propagation in pipelines filled with gelled waxy crude oil, using theoretical [7–15] as well as experimental [2,16,17] methods. However, the effect of thermal heating on pressure wave propagation in real systems has not been investigated. The only notable work on non-isothermal pipe flow containing wax–gel was performed by Vinay et al. [18]. The authors treated wax–gel as an incompressible Bingham fluid. Moreover, they did not consider the convective and viscous dissipation terms. In another study, regularized Bingham rheology for incompressible Poiseuille flow was modelled at non-isothermal conditions. The convective and viscous dissipation terms were considered [19]. However, pressure propagation in pipelines for weakly compressible gels under non-isothermal conditions has not been analyzed previously. In the present study, the effect of convective and viscous dissipation terms is considered along with gel compressibility. Degradation of the gel structure near the wall is provided by differential thermal heating. The weakened gel affords reduced pressure drop requirements for flow restart, which is clearly illustrated and fully accounted for in the current work.

Thermal shrinkage of the liquid fluid holdup may result in formation of gas plugs [20]. Due to the presence of gas plugs the gel is assumed to be weakly compressible. Moreover, it has been reported that even at applied stresses lower than the apparent yield stress, crude oil gel exhibits creeping flow [6,21–23] and

* Corresponding author at: Department of Mechanical Engineering, University of British Columbia, 2054-6250 Applied Science Lane, Vancouver, BC V6T 1Z4, Canada.
E-mail addresses: lalitk@gmail.com, lalitk@mail.ubc.ca (L. Kumar).

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Nomenclature

u, v, w	radial, angular and axial velocities respectively
p	pressure inside the gel
P	applied pressure at the inlet of the pipeline
γ	deformation in the gel
μ	viscosity of the gel
c_p	heat capacity of the gel
K	thermal conductivity of the gel
β	thermal expansion coefficient
χ_Θ	isothermal compressibility of the gel
r, θ, z	radial, angular and axial position respectively
t	represent time
R, L	radius and length of the pipeline
L_s	critical length for flow stop in the case of yielding fluid
W_s	characteristic velocity for scaling
Θ_{wall}	temperature at pipeline wall
Θ_{gel}	initial gel temperature inside the pipeline
τ	stress in the gel
Pe	Peclet number
Br	Brinkman number
Re	Reynolds number
Re^*	modified Reynolds number
δ	compressibility number
μ_r	viscosity ratio of pristine gel ($\gamma \to 0$) to completely broken gel ($\gamma \to \infty$)
α	the ratio of L by L_s
ϵ	ratio of R by L_s
$\Delta\cdot$	divergence operator
m_0	gel degradation coefficient with respect to strain
c	gel degradation coefficient with respect to temperature
$\wedge$	to denote non-dimensional variables

waxy crude oil can be classified as a thixotropic fluid instead of a yielding fluid. Creeping flow is defined by a corresponding high viscosity [6,21–24]. In alternate approach, initial creep can be associated with elastic deformation [25]. However, in this study, initial creeping flow is accounted for by a high viscosity of the gel. At isothermal conditions, creep provides strain in the gel and with increasing strain the gel degrades. The process of gel degradation effects a reduction in the effective viscosity. The low effective viscosity of the waxy gel facilitates flow restart [7,8]. However, at non-isothermal conditions, strain as well as temperature may cause gel degradation, and the temperature effect may be dominant for long pipelines. Gel breakage by consolidated strain (strain buildup over time by continuous application of pressure/stress) is a sequential process for high compressibility gels. For low compressibility gels, strain consolidation is an extremely slow [8] process. In this investigation, a shear history dependent and thermal history dependent high creep viscosity (10^2–10^5 Pa s) is considered. At low strains, viscosity values are similar to Newtonian-Plateau viscosity values.

Gel rheological properties are considered as irreversible because waxy crude oil gel has a very long structural relaxation time (h) compared to pressure propagation time (s). In the current analysis, the very long relaxation time reflects the length of time required to return to an original state after removal of applied stress. At low strain values, the waxy crude oil gel structure may relax subsequent to removal of applied stress (see [26]). However, this phenomenon is limited to extremely low strain values where material breakage is insufficient to affect effective viscosity. Therefore, small order structural relaxation does not influence the pipeline restart process. Moreover, an asymptotic constant effective viscosity value is implemented at low shear strain conditions. The implemented asymptotic limiting value affords consistency of the present rheological model with experimental results at low strain values [26]. It is also reported that, subsequent to gel breakage, the gel strength behaves as a point function of absolute strain (shear history) instead of a point function of time [27,25,28]. Following these known results, the gel viscosity is derived as function of strain and temperature, incorporating an exponential dependency upon strain (γ) as well as temperature inverse (Θ^{-1}). It is known that thermal expansion within a closed system has a large bearing on the magnitude of the pressure field. However in this study, only the limiting value of the isothermal compressibility coefficient is analyzed. This approximation allow sufficient description of the combined effect of pressure (p) and temperature on the fluid density by utilising isothermal compressibility and fluid thermal expansion assumptions.

Viscosity as a function of Θ and γ provides an opportunity to analyze pressure propagation in the gel during thermal degradation due to heat conduction from the side wall. Finally, pressure- and temperature-dependent density correlations enable analysis of the beneficiation effect of additional pressure afforded by gel thermal expansion. The beneficiation effect results in additional flow, thereby promoting restart.

2. Theory

In this study, weakly compressible non-Newtonian fluid flow equations (mass and momentum balances supplemented by non-Newtonian rheological as well as strain evolution equations) are solved together with an energy balance relation. The gel is initially considered to be at a state of repose in the pipeline. At time $t = 0+$, an imposed pressure is applied at the inlet via a displacing fluid (see Fig. 1). The displacing fluid is assumed to be fresh crude oil. Fresh crude oil can be modelled with a very high absolute strain value as well as a high temperature value. Thereby, the displacing fluid is assumed to retain physical properties identical to the pre-gelled crude oil. The thermal condition of the pipeline wall is assumed to be identical to the temperature of the displacing fluid. A finite volume method on a staggered grid is used for solving the governing flow equations. Evolution of strain and pressure is computed for a non-Newtonian fluid at non-isothermal conditions using strain- and temperature-dependent rheological correlations.

2.1. Constitutive equations

In the bounded domain of Ω of $\Re^d$ and time interval $[0, T]$, the governing equations for non-isothermal weakly compressible fluid flow are given as follows.

Conservation of mass:

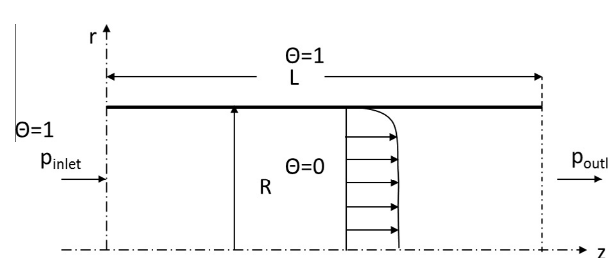

Fig. 1. Schematic diagram showing flow geometry along with boundary condition.