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Start-up flow behavior of pipelines transporting waxy crude oil emulsion

Guangyu Sun[a,b], Jinjun Zhang[a,1,*], Chenbo Ma[a], Xinyi Wang[a]

[a] National Engineering Laboratory for Pipeline Safety/MOE Key Laboratory of Petroleum Engineering/ Beijing Key Laboratory of Urban Oil & Gas Distribution Technology, China University of Petroleum (Beijing), Beijing 102249, China

[b] College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao, Shandong 266580, China

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ABSTRACT

Water-in-waxy crude oil emulsion tends to gelatinize under shutdown conditions when the atmospheric temperature or sea water temperature is lower than its pour point, threatening pipeline restart safety. Based on previous researches about the complex rheological properties of waxy crude oil emulsion gel, elasto-viscoplastic thixotropic models were first compared with each other according to experimental results, and the model proposed by Teng was screened out to be the most accurate one that could describe the whole response after shear loading. Then the effects of rheological changes on pipeline start-up flow after the formation of emulsion gel were computed numerically with the help of this thixotropic model. It was found out through a case study of a 50 km long pipeline that the time for the flow to start and from start state to steady state at terminal of the pipeline transporting 30% water cut emulsion gel increases by 5.8 times and 2.1 times respectively when compared with the time for original crude oil. Meanwhile, the steady flow rate after start-up decreases dramatically by 85.9%. The pipeline transporting waxy crude oil could be restarted successfully at the pressure of 1.0 MPa, while it need to be pressurized to 5.0 MPa to resume flow when its 60% water cut emulsion gel is formed. All these results indicate that the emulsification of waxy crude oil makes pipeline restart more difficult, and the lengthening of the pipeline magnifies the influence of the emulsification. Therefore, the possibility of wax precipitation in crude oil emulsion and further the structural characteristics of the formed emulsion gel have to be taken into consideration during multiphase pipeline shutdown.

1. Introduction

Among petroleum resources exploited globally, both the number of producing areas and the total output of waxy crude oil keep increasing, thus making its pipelining safety an important issue (Frigaard et al., 2007). A major flow assurance challenge is the transportation of high paraffinic crudes in offshore fields where subsea flow lines are involved (Thomason, 2000). In subsea multiphase systems, crude oil, water, and gas usually coexist. Among them, the water comes not only from reservoirs, but also from the waterflooding during secondary and tertiary oil recovery. At the same time, the liquid phase contains dissolved gas, which has an impact on the viscosity (Thomason, 2000). In most cases, there will be a free gas phase present as well (Johnsen and Rønningsen, 2003). On this occasion, the pipe flow cannot be simply characterized as laminar or turbulent flow. In order to acquire the real pressure drop, the distribution and relative quantity of every phase, and further the resulting flow pattern, have to be considered. Quite a few studies have investigated the viscous behavior and pressure drop under the three-phase pipeline flow (Hewitt et al., 1995; Johnsen and Rønningsen, 2003; Pan et al., 1995; Wegmann et al., 2007). When a pipeline shut-down occurs, the light ends except methane in the gas will likely condense and mix with the crude oil phase (Thomason, 2000).

During hot waxy crude oil transportation at low ambient temperature underseas, the challenge is particularly great when the sea water temperature is lower than the pour point of the crude oil being transported. For example, the water temperature is only about 4 °C at the depth of 3000 m below sealevel, while the oil temperature is usually above 50 °C (because waxy crude oil has to be transported above its pour point which is often higher than 30 °C). As a result, very strong heat transfer happens, which may lead to the decrease of oil temperature in pipelines, especially at arranged or accidental pipeline shutdown occasions. Consequently, the solid wax crystals may gradually precipitate from the liquid oil and further joint with each other. Eventually, a crude oil gel is formed with certain structural strength, manifesting complex rheological properties such as viscoelasticity,

* Corresponding author.
E-mail address: zhangjj@cup.edu.cn (J. Zhang).
[1] Present/Current address: Department of Petroleum Storage and Transportation Engineering, China University of Petroleum-Beijing, 18 Fuxue Road, Changping, Beijing 102249, China

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Nomenclature

τ	Total shear stress (Pa)
τ_y	Yield stress (Pa)
τ_{od}	Dynamic yield stress (Pa)
τ_o	Static yield stress (Pa)
$\dot{\gamma}$	Shear rate (s^{-1})
$\dot{\gamma}_{od}$	Shear rate that marks the transition in stress from τ_o to τ_{od} (s^{-1})
γ	Total shear strain (dimensionless)
t	Time (s)
t_{eq}	Characteristic time of the change of λ (s)
λ	Scaled structural parameter (dimensionless)
a	Kinetic constant for structural buildup (s^{-1})
b	Kinetic constant for structural breakdown ($Pa^{-m}\ s^{m-1}$)
G, G_0	Elastic and shear modulus of the completely structured material, respectively (Pa)
γ_e	Elastic strain of the continuous network structure (dimensionless)
γ_{co}	Critical strain for the continuous network (dimensionless)
Δk	Structure-dependent consistency ($Pa{\cdot}s^{n_1}$)
k	Completely unstructured consistency ($Pa{\cdot}s^{n_1}$)
η	Apparent viscosity (Pa s)
$\eta_{st,0}$	Hydrodynamic viscosity increment (Pa s)
η_0	Viscosity of the completely structured material (Pa s)
η_∞	Viscosity of completely broken-down structure (Pa s)
τ_{ss}	Apparent steady state stress (Pa)
λ_{ss}	Steady state value of the structural parameter (dimensionless)
γ_c	Critical value of the elastic strain (dimensionless)
ϕ	Energy dissipation rate, defined as $\phi = \tau\dot{\gamma}$ in simple shear flow ($Pa{\cdot}s^{-1}$)
k_1	Kinetic constant for shear-induced breakdown (s)
k_2	Kinetic constant for shear-induced build-up ($s^{0.5}$)
k_3	Kinetic constant for Brownian build-up (dimensionless)
C_1	Kinetic rate constant of aggregates breaking up into individual particles (s^{n-1})
n, n_1	Kinetic indexes describing the viscous stress's dependence on shear rate (dimensionless)
L_r	Relative amount of individual particles in the form of aggregate (Pa s)
p_1, p_2	Parameters related to the viscoelastic property (dimensionless)
n_2	Positive dimensionless constant (dimensionless)
m, β	Dimensionless constants (dimensionless)
s	A characteristic time with the value of 1 s (s)
K_a', K_a''	Specific agglomeration rate constants (dimensionless and s^{ρ}, respectively)
k_b	Specific breakdown rate constant (dimensionless)
k_0	Brownian motion induced agglomeration rate constant (s^{-1})
τ_w	Shear stress at pipe wall (Pa)
V	Mean flow velocity of pipeline cross section (m/s)
ρ	Density of waxy crude oil emulsion (kg/m^3)
P	Mean pressure of cross section (Pa)
x	Axial location of pipeline (m)
d	Internal diameter of pipeline (m)
α	Speed of pressure wave (m/s)
P_{in}	Entrance pressure of the pipeline (Pa)
P_{out}	Terminal pressure of the pipeline (Pa)
L	Length of the pipeline (m)

yield behavior, structural breakdown characteristics, etc. (Cazaux et al., 1998). These non-Newtonian rheological properties bring significant influences on pipeline start-up flow (Chang et al., 1999). Hence it becomes particularly meaningful to ascertain and further characterize precisely these properties.

In multiphase gathering pipelines, due to the agitation in the wellbore, pipes, pumps, chokes, and valves, the initial separated phases of water and crude oil generally takes the form of emulsion (Keleşoğlu et al., 2012). According to statistics, most of the produced liquid worldwide is recovered in the form of emulsion (Abou-Kassem and Ali, 1995). Therefore, only a small part of water takes the free state in such pipelines, so it is roughly considered that the oil-water flow is homogeneous. Besides, the crude oil emulsion tends to possess good stability, owing to the existence of polar components, like resins and asphaltenes, as natural surfactants (Guo et al., 2015). When it is transported below wax appearance temperature (WAT), the wax molecules in crude oil may precipitate out, adsorbing on droplet surface, or interlinking with each other (Ghosh et al., 2015; Visintin et al., 2008), eventually resulting in the gelation of the emulsion. Within the existing start-up flow calculation models of waxy crude oil pipeline, the effects of crystallized wax are taken into account through yield stress or thixotropy in rheological constitutive models, while its

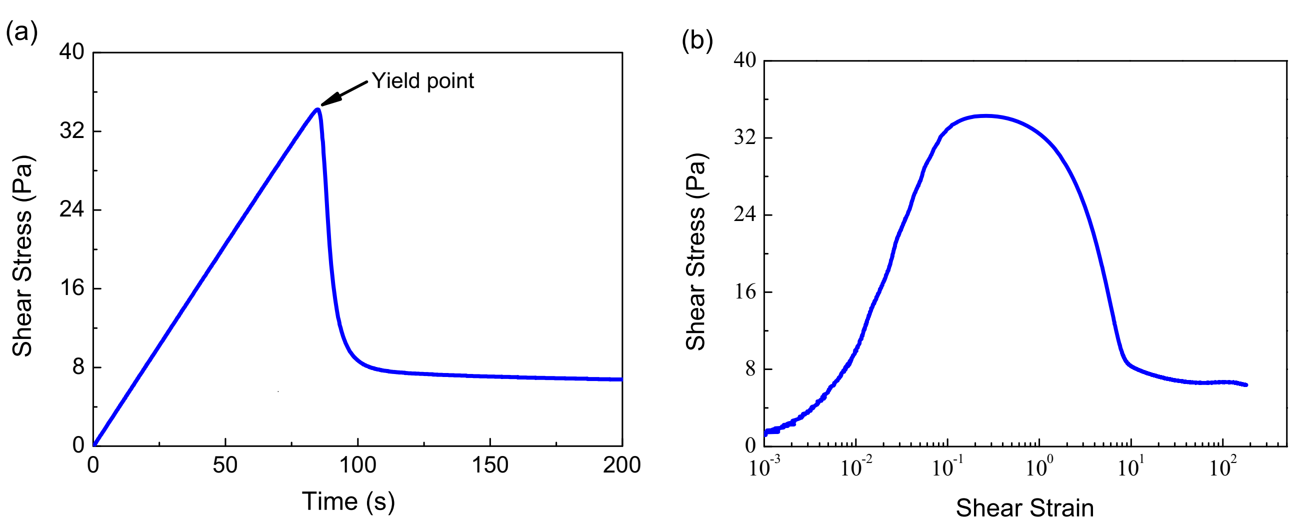

Fig. 1. Stress response of gelled Daqing waxy crude oil after a constant shear rate loading: (a) the evolution of shear stress with loading time; (b) the evolution of shear stress with shear strain.