Research Article

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Prediction of pipeline restart using different rheological models of gelled crude oil

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Abstract: Shutdown of a waxy crude oil pipeline is unavoidable due to maintenance or emergency. It is critical to select the rheological models of gelled crude oil when investigating the pipeline restart process. Three crude oil rheological models are summarized based on previous researches in this paper, which are the viscoelastic model of a viscous type (Model 1), viscoelastic model of an elastic type (Model 2), and pure viscous thixotropic model without yield stress (Model 3). The same rheological data was fitted by the three models respectively. The critical state that pipeline can restart successfully is dominated by the slow creep of the gelled crude oil that can be regarded as an incompressible pipe flow, and this is verified by the pipe restart experiments under constant pressure conditions in this paper. To discuss the effects of the rheological models on calculation of pipeline restart separately, a simplified one-dimensional mathematical model with the pump boundary condition is established. The different calculated flow rate indicates that rheological models affect the judgement of the pipeline restart even though they are fitted from the same rheological data.

Keywords: Gelled crude oil; Pipeline restart; Rheology model; Viscoelastic-thixotropic; Critical state

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1 Introduction

Waxy crude oils are often heated to reduce pressure drop during transportation. For maintenance, emergency or other reasons, the pipeline flow may stop. After long time shutdown of heated waxy crude oil pipelines, oil temperature can greatly decrease. As a result, oil fluidity deteriorates, and pressure required to restart the pipeline increases. Hence, it is necessary to calculate the critical restarting pressure in order to operate waxy crude oil pipelines safely.

Crude oil usually turns into gel showing viscoelastic, thixotropic and other non-Newtonian fluid rheological behaviors under low temperature [1]. Generally, the mechanical response of gelled oil can be divided into three regions: a pre-yield (viscoelastic) region, a yielding (viscoelastic-thixotropic) region, and a post-yield (thixotropic and/or viscous) region [2–4]. Different kinds of crude oils have different mechanical response characteristics due to the contents of wax, gum, and asphaltene. Therefore, selecting the suitable rheological model that can truly describe the flow characteristics of gelled oil is extremely significant for pipeline restart calculations.

In this paper, the effect of the crude oil rheological model expressed by different mechanical analogies on the calculation results of the pipeline critical restart process was studied. According to the types of the mechanical analogies, rheological models are divided into three kinds, the viscoelastic model of the viscous type, the viscoelastic model of the elastic type and the pure viscous thixotropic model without yield stress.

2 Rheological models of crude oil

In early literatures, crude oil was mostly regarded as a viscous fluid to solve the pipeline restart problems. Many researches were conducted on pipeline restart based on the Bingham model [2, 5–7]. The elastic yield stress and static yield stress were used to characterize the initial structural strength of the gelled crude oil. Shear stress mod-
els were put forward by fitting rheological experimental data under constant shear rates [8, 9]. Zhang [10] chose the Dong PS thixotropic model [9] to characterize the shear stress of the gelled crude oil in his research. At present, structural dynamic models, which are well suitable for shear rate changing conditions, have been widely used in the hydraulic calculation of pipeline restart [11, 12]. A 1.5D pipeline restart model was established based on the Houska rheology model [13]. However, structural dynamic models can only describe the process of structural cracking without considering the viscoelastic response stage before the material yielding.

In fact, the shear stress increases with shear strain before yielding for most thixotropic materials under constant shear rate conditions. According to the experimental data [9], it took a quite short time for restarting pressure wave to pass through the whole pipeline at a high wave velocity. So there is no obvious yielding and thixotropy in the gelled oil, and the stress response stage before yielding is much more important. Other scholars also insisted that the initial mechanical response and yielding characteristics of gelled crude oil should not be neglected when the transfer law of restart pressure was studied [14–16]. It is found that the oil stress increases with strain before being thixotropic through the initial restarting mechanical experiment under constant shear rates [17]. Chen Lei presented a mathematical model to characterize the initial stress increment of gelled crude oil at different shear rates by paralleling Maxwell mechanical analog and power-law fluid element [18]. Later, models describing initial viscoelastic properties under constant shear stress were established [19–22]. However, they have not been further applied compared to those with controlled shear rates. To describe the viscoelastic mechanical response before material yielding and thixotropy, Huang, Mujumdar and Dullaert assumed that the total stress were composed of elastic stress $\tau_M$ and viscous stress $\tau_v$, where $\tau_M$ is interrelated with the structural parameter $\lambda$ and strain $\gamma$, and $\tau_v$ is a structure and shear rate dependent parameter [23–26]. The stress increment can be well represented by this kind of rheology model during the initial shear deformation stage. De Souza Mendes treated the total shear stress as the sum of viscous stress $\tau_v$ and a special Maxwell mechanical analog with viscoelastic stress $\tau_M$, which is called the Quasi-Jeffreys model [27, 28]. Teng HX et al. [29] insisted that the models proposed by Mujumdar and Dullaert are more suitable for the gelled crude oil with the fragile structure than the Quasi-Jeffreys models proposed by de Souza Mendes, and then proposed a rheology model under time-dependent shear rates conditions. On the contrary, Chen Lei considered the effect of stress relaxation characteristics on the mechanical response process under constant shear strain conditions and proposed a mechanical response model suitable for large-scale and ultra-low shear rate conditions [18, 30].

Mechanical analogy is widely used to describe the viscoelastic properties of gelled crude oil. The mechanical analogy includes springs and dashpots, which represent the elastic property and viscous property respectively. Structure parameters were also introduced into springs or dashpots to describe the thixotropic properties. In the mechanical analogy, springs can deform instantly when shear stress is applied, but the deformation is finite because of the finite shear stress. Dashpots can deform infinitely when shear stress is applied. As for a mechanical analogy shown in Figure 1, from the left end to the right end, no matter which path is chosen, if there is always at least one dashpot is passed, the mechanical analogy is defined as a viscous type analogy. Otherwise, the mechanical analogy is an elastic type analogy, as shown in Figure 3. Obviously, because of the dashpot, the viscous type analogy can deform infinitely. On the other hand, the elastic type analogy cannot deform infinitely because of the limitation of the spring. In order to describe the infinite deformation or flowability of gelled crude oil, researchers [26, 31] used a specific function to modify the elastic modulus of the spring to ensure that the elastic modulus equals to 0 when the shear deformation is large enough. Because of the significant difference between springs and dashpots, the mechanical analogy of the viscous type differs from the one of the elastic type. Therefore, for different mechanical analogies containing both springs and dashpots describing the viscoelastic properties of gelled crude oil similarly, calculation results of pipeline restart may be significantly different.

### 2.1 Viscoelastic model of viscous type (Model 1)

In this paper, the rheology models proposed by de Souza Mendes [27, 28] and Chen [18, 30] are summarized as Model 1, e.g. the Quasi-Jeffreys model, as shown in Figure 1.

![Figure 1: Mechanical analog of Model 1](image-url)
The Jeffreys model has the flowability that can characterize the stress relaxation of viscoelastic materials for the Maxwell analog. Chen improved this model by introducing a damage variable to characterize the softening process of the materials \cite{18, 30}. The mechanical analogy of the model is presented in Figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{Diagram of the quasi-Jeffreys model}
\end{figure}

The structural recovery process of thixotropic viscous materials was neglected when the initial deformation process of materials was studied \cite{30}. Here, the mathematical equation of shear stress was obtained under the constant shear rate considering the structural recovery process of thixotropic elements, which is expressed as

\begin{equation}
\tau(t) = \left[1 - D(\gamma)\right] \frac{\eta_M \dot{\gamma}}{\eta_M} \left[1 - \exp \left(-\frac{G_M \gamma}{\eta_M} \dot{\gamma}\right)\right] + D(\gamma) (K_0 + \lambda \Delta K) \dot{\gamma}^n
\end{equation}

Where, \( \tau(t) \) is shear stress, Pa; \( t \) is time, s; \( D(\gamma) \) is damage variable; \( \eta_M \) is viscosity, Pa·s; \( \dot{\gamma} \) is shear rate, s\(^{-1}\); \( G_M \) is elastic modulus, Pa; \( \gamma \) is shear strain; \( K_0 \) is unstructured coefficient, Pa·s\(^n\); \( \Delta K \) is structure-dependent consistency, Pa·s\(^n\); \( n \) is the rheology index; \( \lambda \) is the structural parameter can be calculated by Eq. 2.

\begin{equation}
\frac{d\lambda}{dt} = a (1 - \lambda) - b \gamma^m
\end{equation}

Where, \( a \) is the kinetic constant for structure build-up; \( b \) is a kinetic constant for shear-induced breakdown; \( m \) is a dimensionless constant. The damage factor \( D(\gamma) \) can be calculated by Eq. 3.

\begin{equation}
D(\gamma) = 1 - \exp \left[-\left(\frac{\gamma}{\delta}\right)^k\right]
\end{equation}

Where, \( k \) is the shape parameter; \( \delta \) is the scale parameter. In this article, the Quasi-Jeffreys model proposed by Chen \cite{30} is selected as the Model 1 to carry out the following calculation.

2.2 Viscoelastic model of elastic type (Model 2)

The rheology models built by Mujumdar, Dullaert, Teng Houxing and others are summarized as Model 2 \cite{23–26, 31}, which is the Quasi-Kelvin model, and its mechanical analogy diagram is shown in Figure 3.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3.png}
\caption{Mechanical analogy diagram of Model 2}
\end{figure}

The Kelvin model is a classical model to characterize the creep properties of materials but cannot reflect the stress relaxation properties of viscoelastic materials, which means the model has solid properties. Model 2 can be seen as the simplification of Model 1 by removing the sticky dashpot connected to the spring in the Maxwell analogy. The damage factor was considered to represent the process of weakening of spring elements and strengthening of viscoelastic elements during deformation \cite{30}, and the corresponding shear stress expression can be written as follow:

\begin{equation}
\tau(t) = \left[1 - D(\gamma)\right] G_M \gamma + D(\gamma) (K_0 + \lambda \Delta K) \dot{\gamma}^n
\end{equation}

2.3 Pure viscous thixotropic model (Model 3)

Model 2 is further simplified, and only the special viscous element is reserved, which means that Model 3 can only describe the thixotropic process of materials after yielding. The mechanical analogy is shown in Figure 4.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig4.png}
\caption{Mechanical analogy diagram of Model 3}
\end{figure}

The shear stress equation is given by Eq. (5). Different from Model 1 and Model 2, Model 3 has no elastic property.

\begin{equation}
\tau(t) = D(\gamma) (K_0 + \lambda \Delta K) \dot{\gamma}^n
\end{equation}
2.4 Rheological experiment and Parameters of three models

2.4.1 Rheological experiment

In order to discuss the impact of rheological models on restarting calculation results, the rheological data of a gelled crude oil at different shear rates was selected to conduct the parameter fittings for three kinds of models respectively. The basic physical properties of experimental oil samples can be seen in Table 1.

Table 1: Basic physical properties of experimental oil samples

| Property          | Value |
|-------------------|-------|
| Freezing point    | 34    |
| Density (kg/m³)   | 856   |
| WAT (°C)          | 54    |
| Wax content (%)   | 24.69 |
| Asphaltene (%)    | 0.6   |

The rheometer of HAAKE MARS 60 was used to test the rheology of crude oil. Before the test, the rheometer has been operated for 30 min as standby so that the rheometer can reach the optimum working state. At the same time, the cylinder and the measuring rotor were heated together to the initial temperature of the test for 10 min. Then, oil sample was loaded into the cylinder and sheared for 10 min under constant shear rate and constant temperature condition. After that, the test began. Experimental procedure was showed as follow:

\[
\begin{align*}
65°C & \xrightarrow{10s^{-1}, 10min, \text{at constant temperature}} \ 65°C \\
65°C & \xrightarrow{0.2°C/\text{min}, 10s^{-1}, \text{static cooling 2h}} \ 30°C \\
25°C & \xrightarrow{\text{shearing constant shear rate & temperature}} \ 25°C
\end{align*}
\]

2.4.2 Fitting results

The rheological data of crude oil at different temperatures and shear rates was fitted by three models, respectively. The fitting results are shown in Figure 5–Figure 8. The parameters of three models are presented in Table 2–Table 4.

From Figure 5 and Figure 6, it can be seen both Mode 1 and Model 2 can be applied to describe the viscoelastic thixotropic properties. Figure 8 indicates that the thixotropic process of materials can be well fitted by Model 3. Nevertheless, Model 3 cannot describe the stress rising process in the initial period, as shown in Figure 7 and Figure 8. In addition, the shear stress on the fitted curves of Model 3 is higher than that on the rheological curves at the initial shearing stage in Figure 7 and Figure 8.
Table 2: The parameter values in Model 1

| Parameters | Value |
|------------|-------|
| $G_M$ (Pa) | 1999  |
| $\eta_M$ (Pa·s) | $2.691 \times 10^5$ |
| $\delta$ (-) | 0.02956 |
| $k$ (-) | 1.107 |
| $K_0$ (Pa·s$^n$) | 10.6 |

| Parameters | Value |
|------------|-------|
| $\Delta K$ (Pa·s$^m$) | 593.900 |
| $n$ (-) | 0.472 |
| $a$ (-) | 9.849 $\times 10^{-4}$ |
| $b$ (-) | 2.564 |
| $m$ (-) | 7.602 $\times 10^{-2}$ |

Table 3: The parameter values in Model 2

| Parameters | Value |
|------------|-------|
| $G_M$ (Pa) | 1996.465 |
| $\delta$ (-) | 2.956 $\times 10^{-2}$ |
| $k$ (-) | 1.107 |
| $K_0$ (Pa·s$^n$) | 10.6 |
| $\Delta K$ (Pa·s$^m$) | 593.900 |

| Parameters | Value |
|------------|-------|
| $n$ (-) | 0.472 |
| $a$ (-) | 0.001 |
| $b$ (-) | 2.564 |
| $m$ (-) | 0.076 |

Table 4: The value of parameters in Model 3

| Parameters | Value |
|------------|-------|
| $K_0$ (Pa·s$^n$) | 10.39 |
| $\Delta K$ (Pa·s$^m$) | 583.400 |
| $n$ (-) | 0.4837 |
| $a$ (-) | 2.536 $\times 10^{-8}$ |
| $b$ (-) | 2.513 |
| $m$ (-) | 0.0892 |

Table 5: Relative position of pressure transducers

| Relative position | P1-P6 | P2-P6 | P3-P6 | P4-P6 | P5-P6 |
|------------------|-------|-------|-------|-------|-------|
| Length (m) | 27.10 | 21.87 | 14.4  | 12.57 | 7.1   |

Figure 8: The partial graph of rheological data between Model 1 and Model 3

The apparent viscosity of the oil calculated by Model 3 is also higher than the actual apparent viscosity under the same shearing condition, which means that the pressure required for pipeline restart calculated by Model 3 should be higher than the actual required pressure. Hence, there may be a possible case that the pipeline cannot restart successfully according to the calculation by Model 3 while in fact it does. In other words, using Model 3 to predict or judge the pipeline restart should be conservative, which is acceptable for the pipeline safety. Therefore, using Model 3 to fit the rheological data of crude oil and carry out the calculation of pipeline restart may be an appropriate choice because it has fewer parameters.

3 One-dimensional start-up model of a pipeline

3.1 Incompressible creep experiment of gelled crude oil

3.1.1 Experimental device and procedures

The relationship between temperature and physical parameters of crude oil is presented in Table 1. Figure 9 shows the diagram of the experimental apparatus that mainly consists of four basic parts: the experimental pipe system, the power supply system, the circulation water system, and the data acquisition system.

The inner diameter of the loop is 21 mm and the length is 27.36 m. The relative positions of pressure transducers are shown in Table 5.

The peristaltic pump is used to provide pressure for the pre-shearing of the crude oil before shutdown. The circulation water system is designed to control the temperature of the tested oil, and heating or cooling rate. The data acquisition system records pressure, flow rates and temperature. The buffer tank and gas tank are combined to
Table 6: The basic parameter values for calculation

| Parameters | $A_p$ | $B_p$ | $n_p$ | $d$ (m) | $L$ (m) | $\rho_{oil}$ (kg/m$^3$) | $\rho_{in}$ (kg/m$^3$) | $\mu_{in}$ (Pa·s) |
|------------|-------|-------|-------|---------|---------|--------------------------|------------------------|---------------------|
| Values     | 0.5   | 182.9 | 1.5   | 0.1     | 1000    | 856                      | 1000                   | 0.05                |

maintain the constant restart pressure. P1-P6 are six pressure transducers, and V1-V8 are eight valves.

The restart experiments were conducted at 24°C with constant pressures of 400kPa and 150kPa on the inlet of the pipe respectively. Pressure changes measured by each transducer during the pipe restart process are shown in Figure 10.

In Figure 10, point A is the initial time when pressure is put on the inlet of the pipe, and point B is the pressure release time when the pipe restarts successfully. During the pipe restart tests under constant inlet pressure, the outlet of the pipe is open to the atmosphere. When crude oil is expelled from the outlet of the pipe, the pipe restarts successfully, and then the inlet pressure is released. After exerting a constant pressure on the inlet of the pipe, as shown at Point A, the measured pressure of each transducer increases over time and reaches an approximately constant value. When the pressure at the inlet of the pipe is released, as shown at Point B, the measured data of each transducer also decreases instantly. Compared with the experimental
Figure 11: Shear stress of crude oil between adjacent pressure transducers

(a) inlet pressure 400 kPa

(b) inlet pressure 150 kPa

For the incompressible pipe flow with the uniform pipe diameter, the flow rate along the pipe and shear stress on the inner surface of the pipe are uniform. Based on the measured pressure along the pipe, average shear stress on the inner surface of the pipe between every two adjacent pressure transducers is calculated using Eq. (6). The results are shown in Figure 11.

\[ \tau = \frac{\Delta P d}{4\Delta L} \]  

Where, \( \tau \) is the shear stress on the pipe wall, Pa; \( \Delta P \) is the pressure drop in the element, Pa; \( d \) is the inner diameter, m; \( \Delta L \) is the length between the two pressure transducers, m.

It can be seen from Figure 11 that the average shear stresses in different pipe segments change over time at the initial stage, and then become constant gradually. At the initial stage after putting pressure on the pipe inlet, pressure propagates from the inlet to downstream pipe segments. Phillips and Chala mentioned that a few voids could occur for thermal shrinkage when hot oil cooled down, which led to the obvious compressibility [32–34]. This paper believes that the gelled crude oil is compressed and the voids are filled ceaselessly at the initial restart process because of the pressure propagation.

After the pressure propagation stage, the voids inside the crude oil have been compacted. Shear stresses in different pipe segments are slightly different after reaching the constant values in Figure 11(a) but are almost the same in Figure 11(b). It also indicates that the slower the creep of gelled oil inside the pipe is, the closer the shear stresses along the pipe are. As for the critical state at which the pipeline can restart successfully, the time required to restart the pipeline is extremely long. So the crude oil can be regarded as an incompressible fluid in slow pipeline restart conditions.

3.2 Mathematical model for pipeline restart

It has been proved that compressibility is beneficial to the restart processes of pipelines [35, 36]. Therefore, if the pipeline restart is treated as being incompressible, the calculation result is conservative, which is acceptable for pipeline safety. The crude oil is also considered as an incompressible flow in this paper. The reasons are as follows:

1. The restart experiments under constant pressure have proved that the gelled crude oil can be regarded as incompressible flow in the critical state. Effect of the rheological models on determining the critical state becomes the main focus of this paper.
2. In this paper, the emphasis is the effect of rheological models on the calculation results of pipeline restart, and it can be further highlighted by ignoring the oil compressibility.

To simplify the calculation and focus on main research concerns, the following assumptions are made in this paper.

1. Pipe flow during the restart process is incompressible.
2. The injected fluid at the inlet is a Newton fluid, and its viscosity is \( \mu \).
3. The interface between injected fluid and gelled crude oil is planar without mixing.
Based on the above assumptions, a mathematical pipeline restart model is established in the following section.

The gauge pressure is 0 at the terminal, and the boundary condition at the pipeline inlet is the pump condition, as shown in Eq. (7).

\[ P = A_p - B_p Q^{n_p} \]  

Where, \( P \) is outlet pressure of pump, which is the same as inlet pressure of pipeline, MPa; \( Q \) is the flowrate, \( m^3/s; \) \( A_p = 0.5, B_p = 182.9, \) and \( n_p = 1.5 \) are the characteristic parameters of the pump, respectively; \( m_p \) is pumps connected in series, and the boundary condition of the pump can be given by

\[ P_{\text{unit}} = m_p \left(A_p - B_p Q^{n_p}\right) \]  

Where, \( P_{\text{unit}} \) is the pressure supplied by the pumps connected in series, MPa.

The shear rate at the wall surface caused by the flow is approximately expressed as

\[ \dot{\gamma} = \frac{32Q}{\pi d^3} \]  

The strain \( \gamma \) is the integral of the shear rate \( \dot{\gamma} \) on time, which can be obtained by

\[ \gamma(t) = \int_0^t \dot{\gamma}(t') \, dt' \]  

The wall shear stress \( \tau_{\text{oil}} \) produced by the flow of gelled crude oil is a function of the shear rate \( \dot{\gamma} \) and time \( t \). The shear stress caused by the injected fluid in the initial segment of the pipeline is \( \tau_{\text{in}} \). \( \tau_{\text{oil}} \) can be calculated by the aforementioned rheological models, and \( \tau_{\text{in}} \) can be expressed as

\[ \tau_{\text{in}} = \mu_{\text{in}} \dot{\gamma} \]  

Where, \( \mu_{\text{in}} \) is the viscosity of inlet flow, \( Pa \cdot s; \) \( \tau_{\text{in}} \) is the shear stress caused by the injected fluid, Pa. Considering the inertial effects during the unsteady pipeline startup process, de Souza Mendes proposed the relationship between pressure, shear stress and velocity of the fluids in the pipeline startup model in literature \[37\]. Hence, the pressure drop of the entire pipeline at any time step can be calculated by Eq. (12).

\[ P_0 = \frac{4L_{\text{in}} \tau_{\text{in}}}{d} + L_{\text{in}} \rho_{\text{in}} \frac{dv_{\text{in}}}{dt} + \frac{4L_{\text{oil}} \tau_{\text{oil}}}{d} + L_{\text{oil}} \rho_{\text{oil}} \frac{dv_{\text{oil}}}{dt} \]  

Where, \( P_0 \) is the pressure at the starting point of the pipeline, \( Pa; \) \( v_{\text{in}} \) is the velocity of injected fluid, \( m/s; \) \( v_{\text{oil}} \) is the velocity of crude oil in the pipeline, \( m/s; \) \( \rho_{\text{in}} \) is the density of injected fluid, \( kg/m^3; \) \( \rho_{\text{oil}} \) is the density of crude oil in the pipeline, \( kg/m^3; \) \( L_{\text{in}} \) is the length of the pipeline segment filled with gelled oil, \( m; \) \( L_{\text{in}} \) is the length of the pipeline segment filled with injected fluid, \( m; \) \( L \) is the total length of pipeline, \( m. \) \( dv/dt \) represents the acceleration of fluid, \( m/s^2. \)

The total length of the pipeline is \( L = L_{\text{oil}} + L_{\text{in}} + L_{\text{in}}, \) which can be obtained based on the velocity \( v_{\text{in}} \) using Eq. (13).

\[ L_{\text{in}}(t) = \int_0^t v_{\text{in}}(t') \, dt' \]  

For incompressible fluids, the relationship between \( v_{\text{in}} \) and \( v_{\text{oil}} \) is

\[ v_{\text{in}} = v_{\text{oil}} \]  

Table 6 lists the parameters of the pump, pipeline and injected fluid.

The restart processes were simulated for configurations with one pump, three pumps, and five pumps in series, respectively base on the aforementioned three models. And then the changes of flow rates and the length of the pipeline segments filled with the injection fluid were analyzed.

### 3.3 Results of calculation of different models

From Figures 12 to 14, it can be observed that the pipeline can restart smoothly with three-pump or five-pump configurations, and the length of the injected fluid increases gradually. However, pipeline restart processes are different for the three rheological models under the one pump condition.

Figure 15 presents the comparison of the flow rates and the length of the injected fluid calculated by different rheological models. It can be seen from Figure 15 that the calculation results of pipeline restart from different rheological models are significantly different under the one-pump condition. Using Model 1, the viscoelastic model of the viscous type, the calculated flow rate can recover ultimately after a long period of an ultra-low level, and the length of the pipeline segment filled with the injected oil gradually increases. Using Model 2, the viscoelastic model of the elastic type, the flow rate is almost 0 without rising. Using Model 3, a pure viscous model, although the initial shear stress is higher than the actual shear stress shown in Figure 7 and Figure 8, the calculated flow rate
indicates that the pipeline restarts more easily. In other words, the calculation by Model 3 shows that the pipeline can restart successfully, but the result may not agree with the reality. From this point of view, the calculation result from Model 3 is audacious and non-conservative, which disagrees with what is presented in Figure 7 and Figure 8. Therefore, Model 3 is an audacious method to describe the rheology of gelled crude oils in calculating pipeline restart due to no elastic property.

3.4 Discussion on the difference of rheological models

When modelling the rheological properties of the viscoelastic-thixotropic fluid before calculating pipeline restart, researchers typically conduct the tests under shearing conditions, such as the constant shear rate condition [15, 30], stepwise shear rate condition, and time-dependent shear rate condition [29]. Usually, the range of the controlled shear rates in rheology measurements is finite, and the rheological models obtained from the finite experimental data may be used to solve the problems out of the finite range.

Under different pump boundary conditions, the actual pressure at the inlet of the pipeline is different during the pipeline restart process. The pressure at the inlet of the pipeline is calculated under the conditions of one pump, three pumps, and five pumps respectively. Figure 16 presents the results. It is obvious that the pressure at the inlet of the pipeline under one pump and three pumps conditions is approximately constant. Hence, in this study,
the experiments on the critical state were conducted under constant pressure.

Considering the constant pressure at the inlet of the pipeline and the incompressibility of the pipe flow, the actual shear stress applied on the gelled crude oil can be regarded as a constant. According to Eq. (6) and the pressure at the inlet of the pipeline, the shear stress on the inner surface of the pipe was obtained. The shear stress was 12.5 Pa with one pump and 37.5 Pa with three pumps. Therefore, constant shear stress, 37.5 Pa and 12.5 Pa were applied respectively to evaluate the creep behavior of gelled crude oil using different rheological models. The recorded shear strain and shear rate are shown in Figure 17.

When \( \tau = 37.5 \text{ Pa} \), as shown in Figure 17(a), the curves of the shear strain obtained from Model 1 and Model 2 are the same because the shear rate calculated by the two mod-
Figure 17: Shear strain and shear rate change over time under different shear stress conditions

(a) shear strain vs. time when $\tau = 37.5$ Pa
(b) shear rate vs. time when $\tau = 37.5$ Pa
(c) shear strain vs. time when $\tau = 12.5$ Pa
(d) shear rate vs. time when $\tau = 12.5$ Pa

As shown in Figure 17(b), the calculated shear strain and shear rate using Model 3 are different from what were obtained from Model 1 and Model 2 at the initial stage.

When $\tau = 12.5$ Pa, Figure 17(c) demonstrates that the curves of the shear strain obtained from these three models are different. In Figure 17(d), under the low shear stress condition, the ultralow shear rate occurs during the pipeline restart process and is far from the shear rate range controlled in the rheology tests shown in Figure 5 and Figure 6. Therefore, using the rheological models obtained from the finite experimental data to evaluate the problem out of the finite range is inevitable when solving the engineering problems using numerical methods. Figure 5 and Figure 6 indicate that both Model 1 and Model 2 can describe the rheological properties of the hypothetical gelled oil properly in the specific shear rate range. However, at ultralow shear rate that is out of the specific shear rate range significantly, the rheological properties calculated by these two models are different.

The maximum shear stress of the gelled crude oil was also computed under constant shear rate conditions using the three models. The relationship between the maximum shear stress and shear rate is shown in Figure 18.

As shown in Figure 18, the maximum shear stresses $\tau_{\text{max}}$ from Model 1 and Model 2 are the same, but the maximum shear stress from Model 3 is higher when the shear rate is between $0.005 \text{s}^{-1}$ and $5 \text{s}^{-1}$, which agrees with the results shown in Figures 5 to 8. Therefore, Model 1 and Model 2 can describe the rheological data under the constant shear rate conditions in Figure 5 and Figure 6 very well, but the Model 3 can only be used to fit the rheological data in the shear stress decrease stage under the constant shear rate conditions.
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However, when the shear rate is lower than 0.001 s\(^{-1}\), \(\tau_{\text{max}}\) obtained from the three models are greatly different. The order of values is \(\tau_{\text{max}}(\text{Model 2}) > \tau_{\text{max}}(\text{Model 1}) > \tau_{\text{max}}(\text{Model 3})\). In the critical state of pipeline restart, the ultralow shear rate occurs, so the shear stress from Model 3 is the lowest. The calculation results of pipeline restart from Model 3 show the most positive trend in restarting pipeline successfully.

When \(\dot{\gamma} \to 0\), \(\tau_{\text{max}}(\text{Model 1}) \to \tau_0 = 0\) and \(\tau_{\text{max}}(\text{Model 3}) \to \tau_0 = 0\), but \(\tau_{\text{max}}(\text{Model 2}) \to \tau_0 > 0\). \(\tau_0\) is regarded as the static yield stress in literature [38], which is the minimum shear stress required to produce unbounded deformation. Obviously, Model 3 is a pure viscous model with the static yield stress of 0. As for Model 1 that belongs to the viscoelastic model of the viscous type, the static yield stress is also 0. But for Model 2, which is a viscoelastic model of the elastic type, the static yield stress is higher than 0.

Here, the difference between Model 1 and Model 2 is mainly discussed. Literature [30] shows that Model 1 can express the stress relaxation of the gelled crude oil, but Model 2 cannot. On the other hand, Model 2 indicates that the gelled crude oil has a static yield stress greater than 0, but Model 1 does not. Considering the definition of the static yield stress, it cannot be measured directly in experiments. According to the philosophical concept of Heraclitus, “everything flows”, whether the gelled crude oil has a static yield stress or not is a real myth.

If “everything flows” is true, Model 1 is the better one to describe the actual rheology of the gelled crude oil theoretically. But if Model 1 is used to evaluate the pipeline restart process, the gelled crude oil inside the pipeline can flow again even with a very low pipeline inlet pressure because the static shear stress equals to 0. Or, the gelled crude oil can always be replaced by light oils (or other Newtonian fluids) and the pipeline can restart successfully as long as the time period of pipeline restart is long enough. However, a long time period of pipeline restart means a low restart flowrate, which is not recommended for the real pipeline working circumstance because the low pipe flow increases the heat loss from the crude oil to the external environment and may lead to poor flow ability. Moreover, due to the requirement of annual capacity or downstream demand, the pipeline is not allowed to operate at low flow for a long time period. Generally, if the pipeline restart takes too long, it is considered that the pipeline restart fails.

Assuming that the gelled crude oil does have the static yield stress, Model 2 is preferable to evaluate the pipeline restart process. If the pressure at the inlet of the pipeline cannot overcome the static yield stress, the pipeline fails to restart. “Failed pipeline restart” can be found in the calculation results by Model 2, which is more reasonable than by Model 1. For an actual waxy crude oil pipeline, hopefully, the failure of pipeline restart only occurs in the calculation rather than in the actual operation. Compared with Model 1, Model 2 is a conservative and secure choice for simulating the pipeline restart process.

4 Remarks

The pipeline restart process of the gelled crude oil was evaluated using three kinds of rheological models in this paper. The difference among the calculation results was discussed. Conclusions can be drawn as follows.

1. Experimental data of pipeline restart shows that the slower the creep of gelled oil inside the pipe is, the closer the shear stresses along the pipe are. At the critical state that pipeline can restart successfully, the crude oil inside the pipeline can be regarded as an incompressible fluid.

2. The pipeline restart models were established using the three rheological models under pump conditions. The profiles of the calculated flow rates using the three rheological models are significantly different near the critical state even though the parameters in the three models were obtained from the same rheological data. Model 3 is the most audacious model to predict the critical state, while Model 2 is the most conservative.

3. The ultra-low shear rate occurs near the critical state of the pipeline restart causes the different calculated flow rates. The maximum shear stresses obtained
from the three rheological models are also significantly different at ultralow shear rates. Model 2 can express the static yield stress of the gelled crude oil, but neither Model 1 nor Model 3 can. Using Model 2 to evaluate the pipeline restart process is a conservative and secure choice.

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