



**HAL**  
open science

## A Methodology to Investigate Factors Governing the Restart Pressure of a Malaysian Waxy Crude Oil Pipeline

Guillaume Vinay, Petrus Tri Bhaskoro, Isabelle Hénaut, Mior Zaiga Sariman, Astriyana Anuar, Siti Rohaida M. Shafian

► **To cite this version:**

Guillaume Vinay, Petrus Tri Bhaskoro, Isabelle Hénaut, Mior Zaiga Sariman, Astriyana Anuar, et al. A Methodology to Investigate Factors Governing the Restart Pressure of a Malaysian Waxy Crude Oil Pipeline. *Journal of Petroleum Science and Engineering*, 2022, 208, pp.109785. 10.1016/j.petrol.2021.109785 . hal-03601996

**HAL Id: hal-03601996**

**<https://ifp.hal.science/hal-03601996>**

Submitted on 8 Mar 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# A methodology to investigate factors governing the restart pressure of a Malaysian waxy crude oil pipeline

Guillaume **Vinay**<sup>a,\*</sup> [guillaume.vinay@ifpen.fr](mailto:guillaume.vinay@ifpen.fr), Petrus Tri **Bhaskoro**<sup>b</sup>, Isabelle **Hénaux**<sup>a</sup>, Mior Zaiga **Sariman**<sup>c</sup>,  
Astriyana **Anuar**<sup>c</sup>, Siti Rohaida M. **Shafian**<sup>b</sup>

<sup>a</sup>IFP Energies nouvelles, 1&4 av. de Bois Préau, Rueil Malmaison, France

<sup>b</sup>Facilities of Future, PETRONAS Research Sdn. Bhd. (PRSB), Bangi, Malaysia

<sup>c</sup>PETRONAS Project Delivery and Technology (PD&T), Kuala Lumpur, Malaysia

\*Corresponding author.

---

## Abstract

Waxy crude oils account for about 20% of world oil reserves. Wax gelation due to pipeline operating at low ambient temperature, especially in subsea environment, is a worst-case scenario that operators fear most since the gel can potentially block the entire pipeline, if it is not managed early. Restart pressure calculation is the first step to assess severity of gelation and subsequently used to plan for the mitigation strategies which are translated into project CAPEX (Capital Expenditure) and OPEX (Operating Expenditure). Gel characteristic (i.e. rheology behaviour and gel compressibility), operating conditions (oil temperature, ambient temperature and oil flow rate) and pipeline geometry (length and diameter) are known factors governing the restart pressure calculation for a gelled waxy pipeline. Malaysian waxy crude oils are unique and have distinctive rheology which differ from waxy crude oils from other regions mainly due to high gel yield stress of more than 500 Pa with potential failure to recovery from gelation. Hence, accurate restart pressure prediction that account for all the governing factors as well as the interplay between them, are crucial for safe operation and cost-effective mitigation strategies. A conservative approach where the entire gel is assumed to yield simultaneously is frequently used but this simple approach fails to take into account many factors, resulting in an overestimation of the restart pressure. Several improved restart pressure calculation methods have been proposed in literature. In this study, an original methodology developed by IFPEN, has been applied to predict the restart pressure of a Malaysian waxy crude oil pipeline at various conditions. The main benefit of this methodology comes from its ability to consider the conditions under which the gel has been formed, that produces a more realistic description where gel strength varies along a pipeline. The case study highlighted that Conservative laws, assuming a homogeneous gel structure everywhere in the pipe, can overestimate the restart pressure by a factor of up to 100 times than a heterogeneous gel. Thanks to the 2D axisymmetric description of the pipeline gel, we showed that the shape and the location of the gel also impact the restart pressure.

---

## Keywords:

Waxy crude oil, Gelling, Numerical simulation, Rheology, Restart pressure

No keyword abbreviations are available

## 1 Introduction

From an operational viewpoint, transporting waxy crude oil under steady state flowing conditions is not a complicated operation. However, during shutdown process when the pipeline is exposed to severe cold external temperatures, the high wax content of waxy crude oils leads to two types of flow assurance problems related to the interlocking gel-like structure build-up; wax deposition and gelation. Wax deposition occurs at pipe wall when the temperature falls below the Wax Appearance Temperature (WAT) and gelation occurs when temperature further decreases below Pour Point Temperature (PPT) due to the rapid growth of wax crystal network. Once gelled up, a restart pressure is required to break the gel and recover flowing conditions.

Since operational shutdown is unavoidable due to various reasons, oil and gas operators may need to design the pipeline to withstand the required restart pressure and provide a high pressure pump to inject a liquid to break the gel. In this case, a good prediction method is necessary to ensure both cost-effective and optimum pump and pipeline design which have direct impact to the capital (CAPEX) and operational (OPEX) expenditures. The operating conditions required to restart the flow are strongly dependent on the properties of the gel structure, and the shutdown conditions in terms of temperature and flow rate under which the gel has been formed. But, current conservative equation,  $\Delta P = 4\tau_y L/D$  (where  $\tau_y$  denotes the gel yield stress, L the pipe length and D the pipe diameter), does not take into account the effects of the dynamics involved in the operating conditions and the complex rheology behaviour of the gelled oil. As a result, the restart pressure may be over-predicted (Vinay et al., 2009).

In general, several important factors need to be considered to give an accurate restart pressure. Severe cooling process experienced by the oil below PPT may cause thermal shrinkage and eventually produce gas voids (Chala et al., 2018) that confer compressibility properties to the material. The compressibility effect is known to give a positive effect (Davidson et al., 2004) on the restart pressure and is a function of gas void fractions (G. T. Chala et al., 2014). When oil temperature goes below WAT, paraffin components will precipitate forming wax crystals. Below PPT, the crystals will grow rapidly and form a wax network which entraps the liquid oil (gelled up) and cease the flow. It will change the Newtonian behaviour of the fluid into a gel-like viscoplastic and thixotropic material. The amount of trapped oil will affect the gel strength and the required restart pressure. Due to the complex thixotropic behaviour of the gel, cooling scenario also has a strong effect on the wax network, indirectly on the restart pressure. High shear rates experienced by the forming gel reduces the strength and vice versa. Lower cooling rates also tend to reduce the gel strength due to longer shearing duration (Lin et al., 2011). It should be noted that waxy crude oil will not undergo same cooling process along the pipeline and the dynamic change can be observed especially in a long pipeline. During shutdown of a pipeline with a constant external temperature, oil will be cooled down under static conditions at the upstream part of the pipeline whereas oil at the downstream will undergo mixed or dynamic cooling. This leads to a heterogeneous gel structure formation along the pipeline which will dictate the gel strength and the restart pressure (Vinay et al., 2009) (Mendes et al. 2012).

Restart pressure prediction method for power law fluid was proposed by (Ajienka and Ikoku, (1995)). The method initially predicts oil/gel temperature along the pipeline and determines which part of the pipeline is demonstrating Newtonian or non-Newtonian oil/gel behaviour according to the temperature. Following that, the total pressure drops for turbulent and laminar flow as well as for gelled flowlines were evaluated at operating and restart conditions, respectively, considering the pre-determined temperature dependent rheological properties of the oil/gel. Since the method neglects thixotropic and compressibility effects, the method will overestimate the restart pressure.

Restart pressure prediction model for compressible and thixotropic gel was proposed by (Davidson et al., 2004). The model accounts for the physical and rheological properties variation of both incoming and displaced fluids as they flow along the pipeline. This model introduces the concept of a propagating yield front and initial compression flow to capture the effect of yield stress and compressibility of the gel. The results revealed two delay times during restart

process when the applied restart pressure is between the static yield stress and the equilibrium yield stress. The first delay time corresponds to the progressive breakdown of the gelled oil structure during compression flow while the second delay time is due to the time-dependent breakdown of the gel structure. This proves that the flow can be restarted at a lower pressure than predicted by the conservative equation. Unfortunately, the model did not consider the heterogeneous structure of the gel along the pipeline associated with static, mixed and dynamic cooling experienced by the oil/gel during the shutdown process.

A 1.5D numerical model was proposed by (Vinay et al., 2009) to predict the restart pressure of weakly compressible flow of a viscoplastic and thixotropic fluid in pipelines. The model assumed a non-zero velocity component in the direction of the pipe axis but allowed velocity variation both in axial and radial directions. The essence of this method is the use of the Uzawa/augmented Lagrangian algorithm to handle the gel yield stress constitutive equation which has been proven to produce good numerical convergence and accuracy. The Houska model (Houska, 1981) (Sestak et al., 1987) is used to describe both viscoplastic and thixotropic behaviour of the gel. The results showed that the flow can be restarted at a pressure lower than the one predicted via the conservative equation, but the impact of the cooling conditions on the gel structure at the initial stage was not investigated. In (Wachs et al., 2008) and (Vinay, et al 2011), authors developed a method (COLDSTART methodology) that able to take into account both thermal and shear history contributing to the heterogeneous structure of the gel along the pipeline via the structural parameters. It may be considered as the first most complete model for restart pressure prediction/simulation of gelled waxy crude oil in pipeline.

A similar approach was proposed but with new thixotropic model in (Mendes and AuthorAnonymous, 2009) and (Mendes et al., 2012). The thixotropic model considers the breakdown term of the structural parameter as a function of shear stress instead of shear rate. The evolution equation for the structural parameter is developed to be able to represent the steady-state flow curve. Though the model embodied a more sophisticated physics, the model did not consider compressibility effect and its usage poses a challenge from practical point of view since the rheological model requires determination of seven flow curves and six thixotropy parameters.

A more recent restart model was developed for a model oil representing Herschel-Buckley fluid (Sierra et al., 2016). In agreement to the previous works, the results showed a delayed start up flow with avalanche effect. Higher applied pressure reduced delay and gel clearance time while higher incoming fluid viscosity lower the displacement velocity.

All the previous works have demonstrated that gel rheology dictates the restart pressure process. In this paper, the methodology developed by (Vinay, et al 2011) has been applied to a Malaysian waxy crude oil pipeline in order to investigate the impact of various factors governing the restart pressure. This paper is organised as follows: after describing the pipeline configurations, we present the experimental results aiming at characterising the rheological and the structural behaviour of the waxy crude oil during shutdown and restart process. In the next section, the methodology is described in detail and used to determine the initial state. Finally, we present numerical predictions of the restart pressure for different shutdown conditions.

## 2 Malaysian pipeline configuration and operating conditions

### 2.1 Pipeline geometry

The pipeline geometry corresponding to a 7.5 km pipeline, including the insulation layer and the thermal properties are presented in Table 1. The thermal properties have been chosen to produce a  $U_{\text{value}}$  of  $6 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ .

alt-text: Table 1

Table 1



**Q2** Pipeline geometry and thermal properties.

Pipeline length, L	7,500 m
--------------------	---------

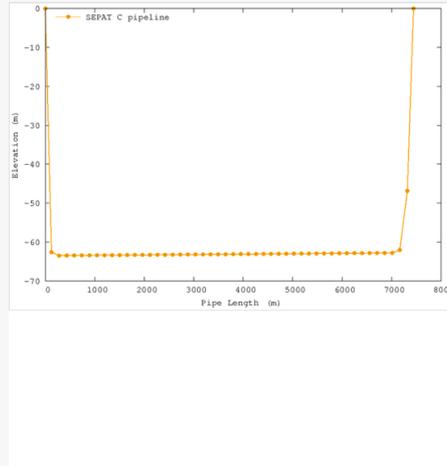
Pipe diameter, D	0.3306 m
Insulation layer thickness, $e_{\text{insulation}}$	0.0127 m
Insulation thermal conductivity, $k_{\text{insulation}}$	0.0734 W.m <sup>-1</sup> .K <sup>-1</sup>

The pipeline bathymetry is shown in Fig. 1.



alt-text: Figure 1

Figure 1



Pipeline bathymetry.

## 2.2 Boundary conditions

The boundary conditions used for simulating the steady state (flowing conditions) are presented in Table 2. Two volumetric flow rates and two ambient seabed temperatures were considered in the study. Two different temperature profiles with respect to the two seabed temperatures were imposed as shown in Fig. 2.

alt-text: Table 2

Table 2

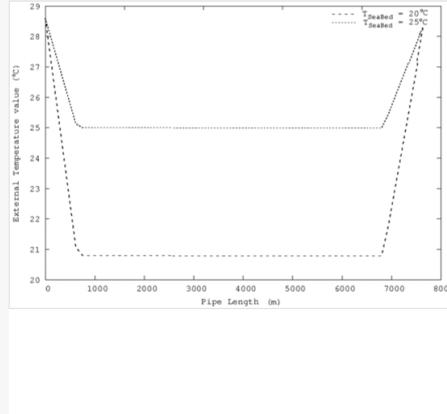


Boundary conditions considered in the study.

Volumetric flow rate, $Q_v$	3500 bbl/day = $6.44 \cdot 10^{-3} \text{ m}^3 \cdot \text{s}^{-1}$ or 25,000 bbl/day = $4.61 \cdot 10^{-2} \text{ m}^3 \cdot \text{s}^{-1}$
Outlet pressure, $P_{\text{out}}$	0 bar
Inlet temperature, $T_{\text{inlet}}$	70 °C
External temperature, $T_{\text{ext}}$	20 °C or 25 °C



Figure 2



Two seabed temperature profiles imposed in the simulation.

To apply the methodology, we need to define the lowest temperature  $T_{\min}$  and the highest temperature  $T_{\max}$  that can be experienced by the oil. In this study, the highest temperature corresponds to the inlet temperature,  $T_{\max} = T_{\text{inlet}} = 70$  C, and the lowest temperature corresponds to the lowest external temperature, i.e.  $T_{\min} = T_{\text{ext}} = 20$  C.

### 2.3 Shutdown scenarios

The restart pressure will be determined after different shutdown scenarios depending on the shutdown time, flow rate  $Q_v$  imposed during steady conditions and seabed temperature  $T_{\text{SeaBed}}$ . Two different shutdown times ( $t_{\text{short}} = 12$  h and  $t_{\text{long}} = 1$  week) will be simulated for different flow rates ( $Q_v = 3500$  bbl/day or  $Q_v = 25,000$  bbl/day) and different sea bed temperatures ( $T_{\text{SeaBed}} = 20$  C or  $T_{\text{SeaBed}} = 25$  C), meaning that 4 different initial states will be eventually tested. The characteristics of the different shutdown scenarios are presented in [Table 3](#).

alt-text: Table 3

Table 3

Initial state features	Length, $L$ (km)	Volumetric crude oil flow rate, $Q_v$ (bbl/day)	Seabed temperature, $T_{\text{SeaBed}}$ (°C)	Shutdown time (hour or week)
Case C-1_Short	7.5	3,500	20	$t_{\text{short}}$
Case C-1_Long	7.5	3,500	20	$t_{\text{long}}$
Case C-2_Short	7.5	25,000	20	$t_{\text{short}}$
Case C-3_Short	7.5	25,000	25	$t_{\text{short}}$

Shutdown scenarios considered in the study.

Initial state features	Length, $L$ (km)	Volumetric crude oil flow rate, $Q_v$ (bbl/day)	Seabed temperature, $T_{\text{SeaBed}}$ (°C)	Shutdown time (hour or week)
Case C-1_Short	7.5	3,500	20	$t_{\text{short}}$
Case C-1_Long	7.5	3,500	20	$t_{\text{long}}$
Case C-2_Short	7.5	25,000	20	$t_{\text{short}}$
Case C-3_Short	7.5	25,000	25	$t_{\text{short}}$

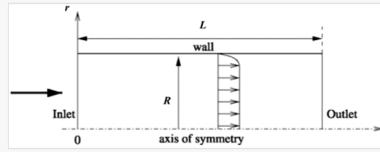
### 2.4 StarWaCS numerical model

All the numerical results presented in this paper are obtained using IFPEN in-house software StarWaCS. StarWaCS is a 1.5D axisymmetric model, based on lubrication assumption, that is a compromise between a 1D approach and a fully 2D axisymmetric formulation. The simplification mainly consists in providing a model that has only one non-zero velocity component in the axial direction of the pipeline which varies both in axial and radial directions. The pressure is constant per cross-section and depends on the axial position only. The flow domain is a 2D axisymmetric pipe geometry described by cylindrical coordinates  $(r, z)$  and shown in [Fig. 3](#). StarWaCS model is fully detailed in ([Wachs et al. 2009](#)).

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 3

Figure 3



Flow domain geometry.

### 3 Material

A severe waxy crude oil from Malaysia is considered in this study. The stabilized/dead oil sample was collected and stored in an 5L IATA compliance container. Basic characteristics of the crude oil are shown in Table 4; the Rheological Gelling Temperature,  $T_{gel}$ , is defined as the temperature below which the rheological behaviour changes.

alt-text: Table 4

Table 4

 The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

Basic properties of the oil.

Density, $\rho$	850 kg.m <sup>-3</sup>
Thermal conductivity, $k_{fluid}$	0.1 W.m <sup>-1</sup> .K <sup>-1</sup>
Heat capacity, $C_p$	2000 J.kg <sup>-1</sup> .K <sup>-1</sup>
Rheological Gelling Temperature, $T_{gel}$	42 °C
Wax Appearance Temperature, WAT	49 °C
Isothermal compressibility coefficient, $\chi_T$	9.10 <sup>-9</sup> Pa

To include temperature and shear history dependencies, two types of experiments are carried out; rheological and structural characterization, which is explained in the next two sub-sections.

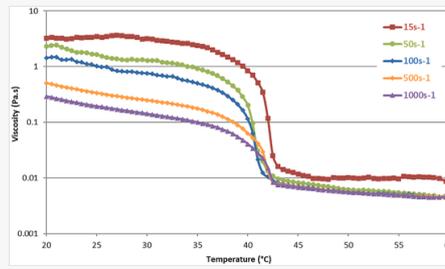
#### 3.1 Rheological characterization of the waxy crude oil during the shutdown process

All rheological tests were conducted with a controlled stress rheometer (DHR3 from TA instruments) with a 4 cm rough plate and plate geometry and a gap set at 300  $\mu$ m. The applied temperature ranges from  $T_{max} = 70^\circ\text{C}$  to  $T_{min} = 20^\circ\text{C}$  with a cooling rate equal to  $-1^\circ\text{C}/\text{min}$ . Viscosity measurements were performed during the cooling of the sample at 5 different shear rates: 15, 50, 100, 500 and 1000  $\text{s}^{-1}$ , as illustrated in Fig. 4. These preliminary rheological tests were conducted to evaluate the rheological behaviour of the oil at various temperatures and shear rates corresponding to thermal and flowing conditions involved in the pipeline under steady state conditions.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 4

Figure 4



Viscosity measurements during cooling at 1 °C/min under various shear rates.

As presented in Fig. 4, there is a dramatic change of the rheological behaviour at  $T_{gel} = 42$  °C. At temperatures above  $T_{gel}$ , the viscosity increases slightly with temperature but does not change with shear rate; so, the oil behaves as a Newtonian fluid at temperature above  $T_{gel}$ . Below  $T_{gel}$ , viscosity increases tremendously, especially at low shear rates and exhibits a non-Newtonian behaviour. The 27 °C difference between  $T_{gel}$  and WAT shows that a certain amount of wax crystals is required to induce a non-Newtonian behaviour.

We model the waxy crude oil under flowing conditions (steady state) as a Herschel-Bulkley fluid characterized by a yield stress  $\tau_y$ , a consistency  $k$  and a shear thinning index  $n$ :

$$\tau = \tau_y + k\dot{\gamma}^n$$

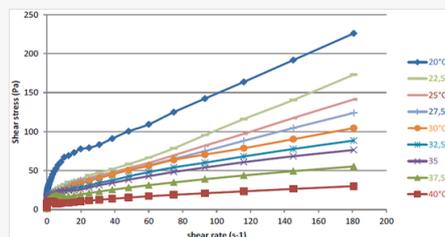
Eq. 1

Since the fluid is flowing in a non-isothermal environment, we make these parameters vary with the temperature. These parameters are determined using flow curves (shear rate sweeps) displayed in Fig. 5. Flow curves are obtained after a dynamic cooling at a shear rate of 100 s<sup>-1</sup> from 70 °C down to 9 different final temperatures (40; 37,5; 35; 32,5; 30; 27,5; 25; 22,5 and 20 °C). The shear rate of 100s<sup>-1</sup> has been chosen as the minimum shear that gives reliable and consistent measurements. Indeed, since this waxy crude oil exhibits a very high consistency, carrying out cooling experiments at lower shear rate makes the measurement difficult and less reliable.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 5

Figure 5

Flow curves obtained after a dynamic cooling at 1 °C/min with a shear rate of 100 s<sup>-1</sup>.

By fitting each flow curve of Fig. 5 using Herschel-Bulkley model (Eq. 1), we then extract the three parameters ( $\tau_y$ ,  $k$  and  $n$ ) for each temperature in Table 5. Linear interpolations will then be used in Section 4 to calculate the temperature in the pipeline under steady state conditions with StarWaCS software.

alt-text: Table 5

Table 5

 The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

Herschel-Bulkley parameters obtained at various temperatures after dynamic cooling at 1 °C/min and a shear rate of 100 s<sup>-1</sup>.

Herschel-Bulkley parameters			
T°C	$\tau_y$ (Pa)	k (Pa.s)	n
40	6.5	0.3	0.83
37,5	6.7	2.6	0.55
35	5.6	5.1	0.49
32,5	4.9	5.7	0.5
30	3.4	6.1	0.54
27,5	4.5	5	0.6
25	5.1	4.6	0.63
22,5	6.6	3.4	0.73
20	12.1	13.7	0.5

### 3.2 Characterization of the structure of the gelled waxy crude oil during the shutdown process

The structure of the waxy gel is described using the elastic modulus  $G'$ , measured using oscillatory tests at an oscillation frequency of 10Hz and an amplitude strain of 0.001%. To take into account the mechanical and thermal history, the evolution of  $G'$  is determined under different cooling scenarios:

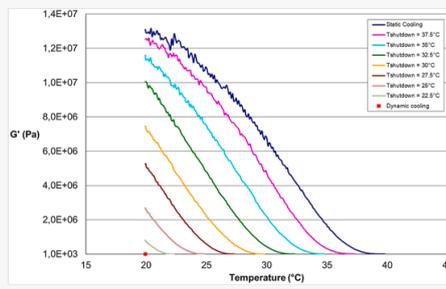
- During a static cooling scenario where the sample is cooled down at rest from  $T_{\max} = 70^{\circ}\text{C}$  to  $T_{\min} = 20^{\circ}\text{C}$  at 1 °C/min.
- After a dynamic cooling scenario where the sample is cooled down under a shear rate of 100 s<sup>-1</sup> at 1 °C/min from  $T_{\max} = 70^{\circ}\text{C}$  to  $T_{\min} = 20^{\circ}\text{C}$ .
- During a mixed scenario consisting in a two-step cooling scenario: an initial dynamic cooling from  $T_{\max} = 70^{\circ}\text{C}$  down to several shutdown temperatures  $T_{\text{shutdown}}$  below  $T_{\text{gel}}$  (37.5, 35, 32.5, 30, 27.5, 25 and 22.5 °C), followed by the measurement of  $G'$  during a static cooling from  $T_{\text{shutdown}}$  to  $T_{\min} = 20^{\circ}\text{C}$ .

The evolution of elastic modulus,  $G'$ , under various scenarios is presented in Fig. 6.  $G'$  is only measured during the static part of the different cooling scenarios. We observe that the strength of the gel increases with the static part of the cooling. Indeed, the elastic modulus  $G'$  is much larger after a static cooling than after a mixed scenario or a full dynamic cooling.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 6

Figure 6



Elastic modulus  $G'$  measured during different cooling scenarios.

### 3.3 Rheological characterization of the waxy crude oil during the restart process

Though the Herschel-Buckley model is used to represent the rheological behaviour of the waxy crude oil during the cooling process, Houska model (Houska, 1981) is chosen to capture the thixotropic behaviour of the gel during the restart process. In the Houska model, described by Eq. 2 and Eq. 3, the yield stress (respectively consistency) comprises a permanent part  $\tau_{y0}$  (respectively  $k$ ) and a thixotropic part  $\tau_{y1}$  (respectively  $\Delta k$ ). The structure of the material is governed by the structural parameter  $\lambda$  which lies in the range  $[0,1]$ ; 0 means that the structure is fully broken down and 1 means that the material is fully structured or gelled. The evolution of the structural parameter  $\lambda$  relies on the transport equation Eq. 3 with a source term containing the generalized shear rate, meaning that the structure breakdown is driven by the shear. In this equation, the “ $a$ ” parameter stands for the build-up rate parameter, the “ $b$ ” parameter for the breakdown rate parameter and the “ $m$ ” parameter is a data fitting parameter.

$$\tau = (\tau_{y0} + \lambda\tau_{y1}) + (k + \lambda\Delta k)\dot{\gamma}^n \quad \text{Eq. 2}$$

$$\frac{d\lambda}{dt} = a(1 - \lambda) - b\lambda\dot{\gamma}^m \quad \text{Eq. 3}$$

A new set of rheological tests is conducted at  $T_{\min} = 20$  °C to determine the eight Houska parameters (as presented in Table 6). The experimental methodology explained in (Houska, (1981)) and (Vinay, (2005)) is adopted to measure these parameters.

alt-text: Table 6

Table 6

*i* The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

Houska parameters value at  $T_{\min} = 20$  °C.

$\tau_{y0}$ (Pa)	27
$\tau_{y1}$ (Pa)	21000
$k$ (Pa.s <sup>n</sup> )	0.29
$\Delta k$ (Pa.s <sup>n</sup> )	5
$n$	0.87
$a$ (s <sup>-1</sup> )	$4.10^{-8}$
$B$ (s <sup>m-1</sup> )	1.04
$m$	0.004

## 4 Evaluation of the structure of the gelled waxy crude oil after the cooling process

Waxy crude oils are deemed to be thixotropic material in the sense that their rheological properties (viscosity and yield stress) depend on mechanical and temperature history. The level of viscosity and yield stress are affected by the temperature and shear-rate at which the material is subjected to, but also by the way in which it has been cooled down and its entire shear-rate history. The level of gelling, or structuring, which determines the viscosity and yield stress magnitude, is often modelled by a structural parameter,  $\lambda$ .

Irrespective of the restart rheological model being used, one essential information for a successful estimate of the restart pressure is to obtain a good assessment of the gel structure along the pipe at the initial state of the restart process. After the flow stops, a heterogeneous gel structure may form inside the pipe, making difficult to have a precise estimate of the length averaged yield stress to be used in the classical force balance model, or any other model, for calculating the restart pressure. An incorrect characterization of the restart initial condition is believed to be the major source of error in the restart pressure calculation, and not the restart model.

So the aim of the three-step methodology detailed in this section, is to provide an accurate description of the gel structure at the initial restart time, i.e. the structure parameter  $\lambda$  after the cooling process, whatever the restart rheological model is. The only characteristic required for the restart rheological model is to be based on a structure parameter.

### 4.1 Description of the temperature field ( $T_{\text{shutdown}}$ ) in the pipeline at shutdown time ( $t_{\text{shutdown}}$ )

This step aims at calculating the temperature  $T_{\text{shutdown}}(r,z)$  anywhere in the pipeline at radial ( $r$ ) and axial ( $z$ ) direction at shutdown time ( $t_{\text{shutdown}}$ ), i.e. when the flow is stopped. When the oil temperature drops below  $T_{\text{gel}}$ , the temperature dependent viscoplastic flow will be simulated using the Herschel-Bulkley model and the rheological parameters of the oil are presented in Table 5. Since a straightforward correlation between these parameters and temperature cannot be deduced, linear interpolation technique was used to determine the value according to the table over the temperature range in the pipeline.

To check that the temperature-dependent Herschel-Bulkley model is able to well describe the behaviour of a waxy crude oil during a cooling under flowing conditions, we compare in Fig. 7 (black dotted curve) the apparent viscosity presented in Fig. 4 and the apparent viscosity  $\mu_a$  recalculated with Eq. 4 using interpolated Herschel-Bulkley data of Table 5.

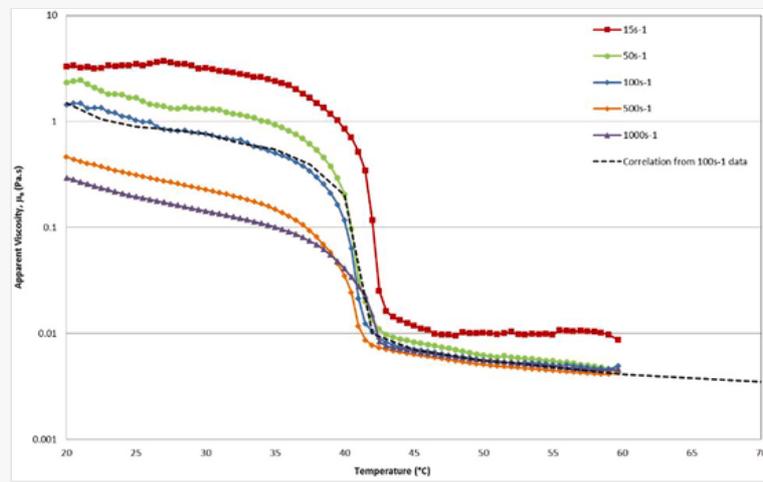
$$\mu_a = \frac{\tau(T)}{\dot{\gamma}} = \frac{\tau_{y0}(T) + k(T)\dot{\gamma}^{n(T)}}{\dot{\gamma}}$$

Eq. 4

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 7

Figure 7



Temperature evolution of apparent viscosity for different shear rates.

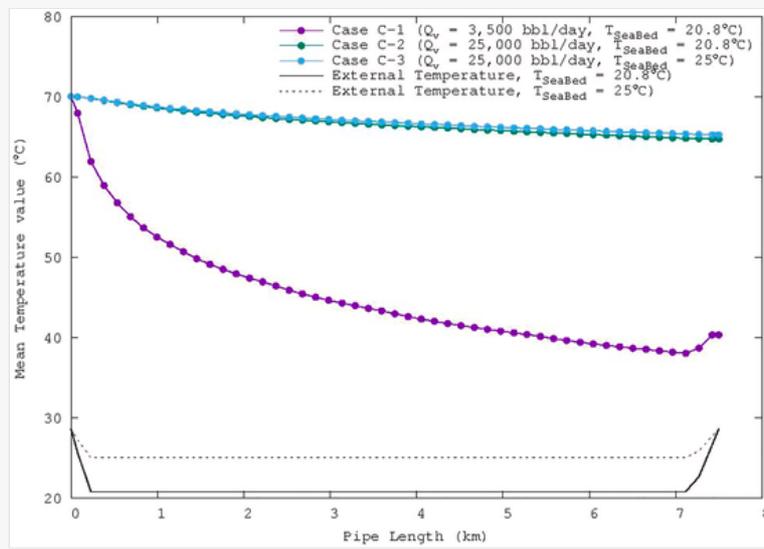
We clearly see that the Hershel-Bulkley data measured after a dynamic cooling at  $100 \text{ s}^{-1}$  (black dotted curve of Fig. 7) well fit the viscosity curve obtained after a dynamic cooling at  $100 \text{ s}^{-1}$  (blue curve of Fig. 7).

Using the temperature dependent Hershel-Bulkley model in StarWaCS software, we simulate the thermal steady state under different conditions detailed in Table 3. In Fig. 8, we plotted the mean temperature profile along the pipeline at steady state, corresponding to the shutdown time, for Case C-1, Case C-2 and Case C-3. We observed the impact of the flow rate on the temperature profile at steady state conditions; the greater the flow rate, the higher the fluid temperature along the pipeline. The impact of the external temperature is not as much as compared to the impact of the flow rate. We indeed observed an increase of the mean temperature of the fluid along the pipeline when the external temperature is higher, but this increase is not significant.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 8

**Figure 8**



Mean temperature ( $T_{\text{shutdown}}$ ) along the pipeline at steady state for Case C-1 ( $Q_v = 3500$  bbl/day,  $T_{\text{SeaBed}} = 20^\circ\text{C}$ ), Case C-2 ( $Q_v = 25,000$  bbl/day,  $T_{\text{SeaBed}} = 20^\circ\text{C}$ ) and Case C-3 ( $Q_v = 25,000$  bbl/day,  $T_{\text{SeaBed}} = 25^\circ\text{C}$ ).

#### 4.2 Description of the temperature field ( $T_{\text{restart}}$ ) during the holding time from shutdown time ( $t_{\text{shutdown}}$ ) to restart time ( $t_{\text{restart}}$ )

The objective of this step is to determine the temperature field  $T_{\text{restart}}(r,z)$  anywhere in the pipeline at time  $t_{\text{restart}}$ , i.e. at the end of the shutdown period. The shutdown period corresponding to the cooling down of the waxy crude oil when the flow is at rest, is defined as  $t_{\text{restart}} - t_{\text{shutdown}}$ , and will be varied between 12 h and 1 week, accordingly as per Table 3.

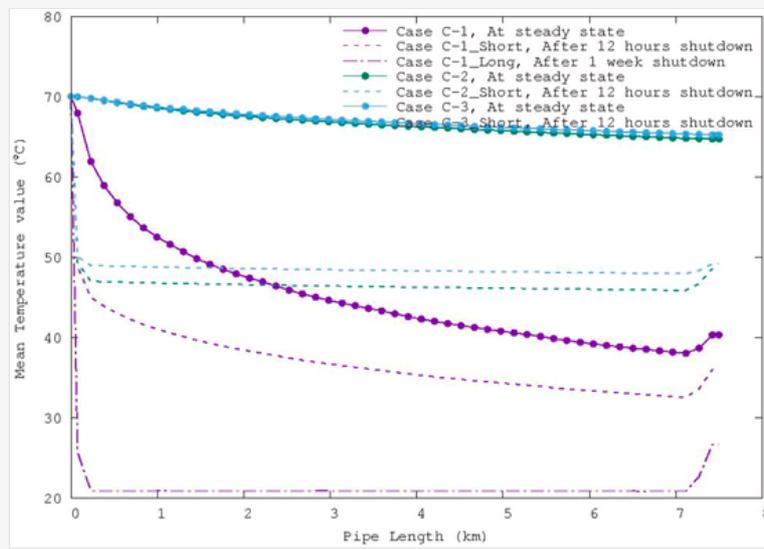
We then simulate the four different initial thermal states corresponding to the four different cooling conditions described in Table 3. To determine the temperature field  $T_{\text{restart}}(r,z)$ , we run a transient thermal calculations with no flow starting from the steady state computed in the previous step and detailed in Section 4.1.

Fig. 9 presented the mean temperature profile along the pipeline at various shutdown time ( $t_{\text{shutdown}}$ ) and after different shutdown periods ( $t_{\text{restart}}$ ) for all the different cooling cases. We observed that after a 12 h shutdown and for the low flow rate case (C-1\_Short), the mean temperature in the pipeline decreases below the gelling temperature,  $T_{\text{gel}} = 42^\circ\text{C}$ . However, increasing the flow rate from 3500 bbl/day to 25,000 bbl/day allows the mean temperature to stay constant along the pipeline and above  $T_{\text{gel}}$ . Also, after a 12 h shutdown, increasing the external temperature from  $20^\circ\text{C}$  to  $25^\circ\text{C}$  shows only to a slight increase of the mean temperature along the pipeline.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 9

Figure 9



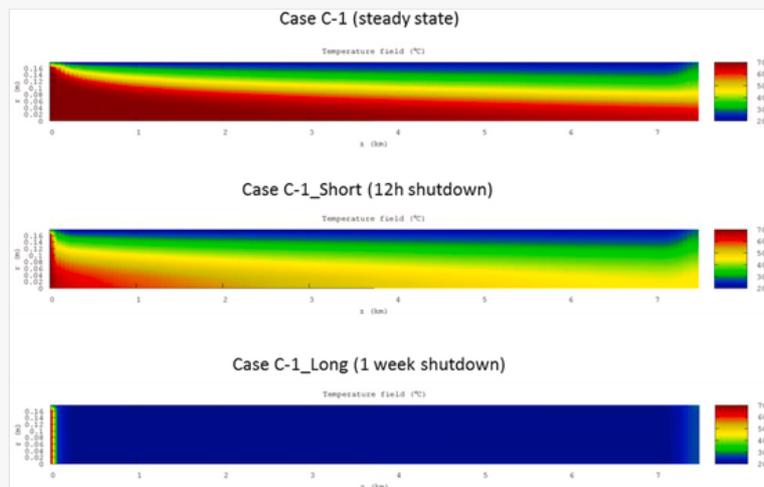
Mean temperature along the pipeline at steady state and after different shutdown periods, for different conditions (Cases C-1, C-2 and C-3).

We then present in Fig. 10, Fig. 11 and Fig. 12 the 2D axisymmetric temperature field ( $T_{\text{shutdown}}$ ) in the pipeline at steady state ( $t_{\text{shutdown}}$ ) and the 2D axisymmetric temperature field ( $T_{\text{restart}}$ ) after different shutdown periods ( $t_{\text{restart}}$ ) for Case C-1, Case C-2 and Case C-3, respectively. The horizontal axis corresponds to the axial distance “z” of the pipeline and the vertical axis corresponds to the radius “r”; “r = 0” corresponds to the center of the pipeline, and “r = 0.1653” corresponds to the pipeline wall.

Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 10

**Figure 10**

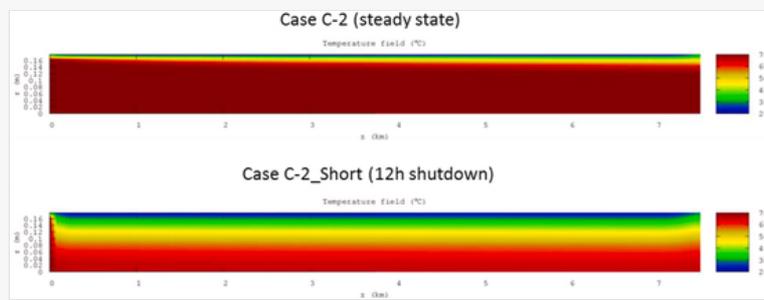


2D axisymmetric temperature field ( $T_{\text{shutdown}}$ ) in the pipeline at steady state and 2D temperature field ( $T_{\text{Restart}}$ ) after different shutdown periods (Cases C-1,  $Q_v = 3500$  bbl/day,  $T_{\text{SeaBed}} = 20^\circ\text{C}$ ).

Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 11

**Figure 11**

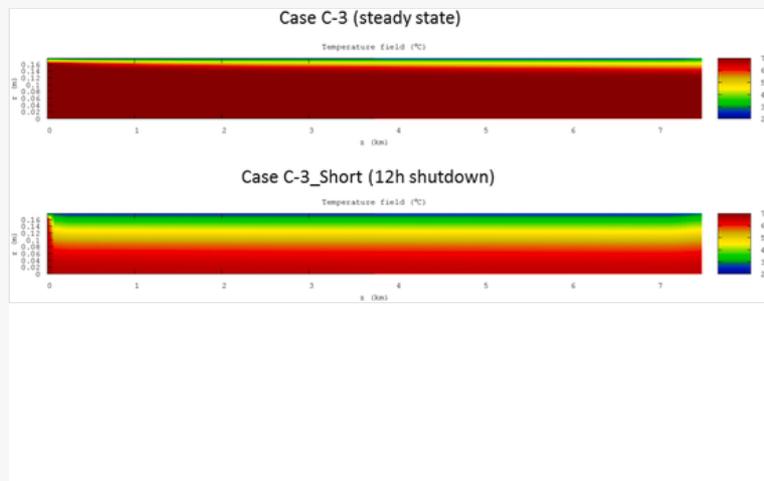


2D axisymmetric temperature field ( $T_{\text{shutdown}}$ ) in the pipeline at steady state and 2D temperature field ( $T_{\text{Restart}}$ ) after a 12h shutdown (Cases C-2,  $Q_v = 25,000$  bbl/day,  $T_{\text{SeaBed}} = 20^\circ\text{C}$ ).

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 12

Figure 12



2D axisymmetric temperature field ( $T_{\text{shutdown}}$ ) in the pipeline at steady state and 2D temperature field ( $T_{\text{Restart}}$ ) after a 12h shutdown (Cases C-3,  $Q_v = 25,000$  bbl/day,  $T_{\text{SeaBed}} = 25^\circ\text{C}$ ).

Obviously, the temperature in the pipeline decreases with increasing shutdown time. After a shutdown of 1 week, the temperature in the pipeline is constant and equal to the external temperature, as observed in Fig. 10 (Case C1\_Long). In Figs. 11 and 12, we observe that thanks to the higher flow rate imposed at steady state, the cooling is mostly a pure thermal conduction after the shutdown, leading to a 2D temperature field with only radial variation.

### 4.3 Description of the gel structure at the initial state

The objective of this step is to determine the structure of the gel after the cooling process. The gelled waxy crude oil has a complex and non-homogeneous structure due to thermal and mechanical conditions at which the oil has been transported, cooled down and stopped. So, the description of the initial state has to be done through the determination of the structure parameter field  $\lambda(r; z)$  by taking into account the thermal and mechanical history (cooling scenario and final temperature).

To do so, we assume that  $\lambda = 1$  represents the strongest gel structure, i.e. a gel that has undergone a static cooling to the lowest temperature in the pipeline ( $T_{\text{min}} = 20^\circ\text{C}$ ). Based on this assumption, the  $\lambda$  values are ranged between two extreme scenarios:

- Dynamic scenario that corresponds to a weak gel structure (low yield stress) characterized by low values of  $\lambda$ ,
- Static scenario that corresponds to a strong gel structure (large yield stress) characterized by high values

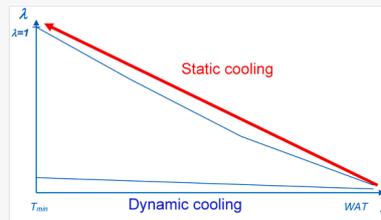
of  $\lambda$ .

This  $\lambda$  representation at which the cooling scenarios and the final temperature are both taken into account, is illustrated in Fig. 13  $\lambda$  values lie between the two main curves; the lower curve corresponds to a completely dynamic cooling, at which the structure of the gelled crude oil is the weakest and the higher curve corresponds to a completely static cooling at which the structure of the gelled crude oil is the strongest.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 13

Figure 13



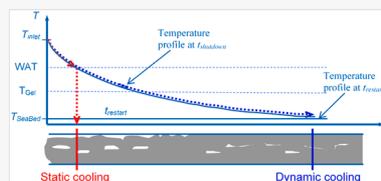
Representation of  $\lambda$  taking into account the thermal and mechanical history of the gel structure.

At initial state of the restart process (at the end of the shutdown process), the structure of the gelled waxy crude oil is heterogeneous since cooling scenarios and external temperatures are different along the pipeline. This observation is illustrated in Fig. 14 for a simplified pipeline where the temperature of the gelled oil at the restart time ( $T_{restart}$ ) is constant and equal to the seabed temperature  $T_{SeaBed}$  ( $T_{restart} = T_{SeaBed}$ ).

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 14

Figure 14



Temperature profile and heterogeneous gel plug description at the initial restart time.

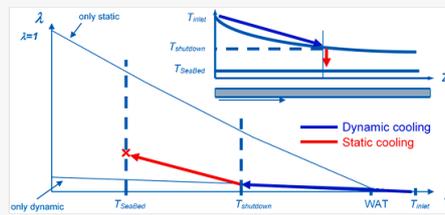
In this case, the gelled oil close to the pipe inlet has undergone a pure static cooling; it has been cooled at rest from a temperature larger or equal to the WAT. However, the gel at the pipe outlet has undergone a dynamic cooling since it has been cooled down to external temperature under flowing conditions. Finally, the gelled waxy crude oil in the middle of the line has been cooled under both dynamic and then static conditions; it is a mixed scenario.

Using the representation of the structure parameter detailed above,  $\lambda$  varies throughout the pipe and it is possible to have a different value of  $\lambda$  at each point of the pipeline. Let us illustrate the determination of  $\lambda$  in the middle of the pipeline using Figure 15.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 15

Figure 15



Representation of  $\lambda$  in the pipeline considering the thermal and mechanical history.

At this middle pipe section, since the sample undergoes a dynamic cooling from  $T_{inlet}$  to  $T_{shutdown}$ ,  $\lambda$  varies following the dynamic curve on Fig. 15 (blue curves). Then, the flow is stopped, and the temperature decreases until to reach the external temperature,  $T_{SeaBed}$  (red curves). The structure of the gel becomes stronger with the temperature decrease until to reach a state corresponding to a value of  $\lambda$  lying between the 2 extreme curves (red cross of Figure 15).

**Remark:** At one temperature, several states of gel structure can occur and so several values of  $\lambda$  are possible, depending on the cooling scenario (dynamic, static or mix scenario). As illustrated in Fig. 15, at temperature  $T_{SeaBed}$ ,  $\lambda$  is indeed lower after a pure dynamic cooling than after a static cooling. Thus, the mechanical history is also well taken into account in this original description of the gel structure at the initial state.

Finally, we need to establish a relation between  $\lambda$  and the two temperatures ( $T_{shutdown}$ ,  $T_{restart}$ ) to properly describe the gel structure at the initial restart time. Thus, we suggest to determine the function  $\lambda(T_{shutdown}, T_{restart})$  that is able to give a fair representation of the structure parameter in the entire pipeline, knowing that the temperature fields  $T_{shutdown}(r,z)$  and  $T_{restart}(r,z)$  are determined in Sections 4.1 and 4.2. We now propose an experimental protocol to determine the function  $\lambda(T_{shutdown}, T_{restart})$ .

The protocol for the determination of the structure parameter  $\lambda$  is based on the measurement of elastic modulus  $G'$  presented in Section 3.2.  $\lambda$  is defined by Eq. 5 as the ratio between the elastic modulus  $G'$  measured for the current cooling scenario (static, dynamic or mix scenario) and the elastic modulus  $G'_{static}$  measured for a static cooling at the coldest temperature  $T_{min}$ :

$$\lambda = \frac{G'}{G'_{static}}$$

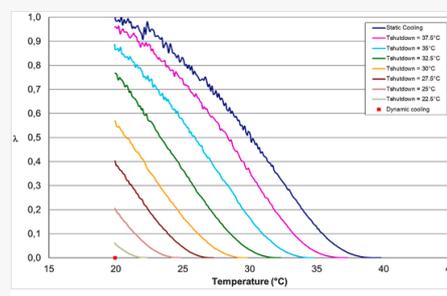
Eq. 5

Thus, the strongest structure of gel (i.e.  $\lambda = 1$ ) is properly defined for the most severe scenario, i.e. after a static cooling to  $T_{min}$ . From  $G'$  measurements displayed in Fig. 6 and from Eq. 5, we obtain the structure parameter  $\lambda$  for different cooling processes, as illustrated in Figure 16.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 16

Figure 16

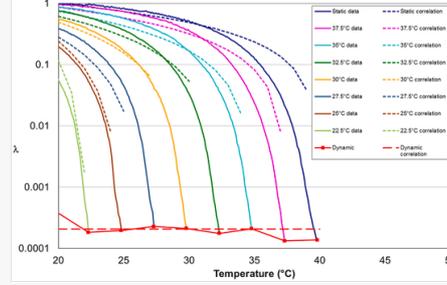


In Fig. 17, we plot the evolution of the structure parameter  $\lambda$  determined from  $G'$  measurements (continuous lines) and from the correlations Eq. 6 and Eq. 7 (dotted lines).

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 17

Figure 17



Evolution of the structure parameter  $\lambda$  with temperature for different cooling scenarios: measurements (plain lines) and correlations defined by Eq. 6 and Eq. 7 (dotted lines).

Then, for each scenario, a correlation is established:

- Dynamic scenario: the dynamic cooling curve (red curve) is reconstructed from the first points of the static part of each mix scenario as illustrated in Fig. 17. Since the lambda values remains almost constant after a dynamic cooling, we propose Eq. 6 for representing the temperature variation of structure parameter  $\lambda$  during a dynamic cooling scenario.

$$\lambda = \lambda_{\text{Dynamic}} = 2.0667 \cdot 10^{-4}$$

Eq. 6

- Mixed and static scenarios: a single fitting law is established to represent the cluster of curves corresponding to the mixed and static scenarios of Figure 17.

$$\lambda = \lambda_{\text{Mix}}(T_{\text{shutdown}}) \left( 1 - \frac{T_{\text{restart}} - T_{\text{min}}}{T_{\text{shutdown}} - T_{\text{min}}} \right)^{\beta_{\text{Mix}}(T_{\text{shutdown}})}$$

Eq. 7

where

$$\lambda_{\text{Mix}}(T_{\text{shutdown}}) = - \left( 1 - \lambda_{\text{Dynamic}} \right) \left( \frac{T_{\text{gel}} - T_{\text{shutdown}}}{T_{\text{gel}} - T_{\text{min}}} \right) + 1$$

$$\beta_{\text{Mix}}(T_{\text{shutdown}}) = \left( \beta_{\text{Mix}}(T_{\text{min}}) - \beta_{\text{Static}} \right) \left( \frac{T_{\text{gel}} - T_{\text{shutdown}}}{T_{\text{gel}} - T_{\text{min}}} \right) + \beta_{\text{Static}}$$

$$\beta_{\text{Mix}}(T_{\text{min}}) = 2.2$$

$$\beta_{Static} = 1.0$$

Finally, the determination of the structure parameter  $\lambda_0(r, z)$  at the initial state is a function of  $T_{shutdown}(r, z)$  and  $T_{restart}(r, z)$  and is defined by the general correlation Eq. 8:

- If  $T_{restart} > T_{Gel}$

$$\lambda_0(r, z) = 0$$

- Else

- If  $T_{shutdown} > T_{gel}$  (Static cooling) or if  $T_{restart} < T_{shutdown}$  (Mixed cooling)

$$\lambda_0(r, z) = \lambda_{Mix}(T_{shutdown}) \left( 1 - \frac{T_{restart} - T_{min}}{T_{shutdown} - T_{min}} \right)^{\beta_{Mix}(T_{shutdown})} \quad \text{Eq. 8}$$

$$\lambda_0(r, z) = \lambda_{Dynamic} = 2.0667 \cdot 10^{-4}$$

- Else if  $T_{restart} = T_{shutdown}$

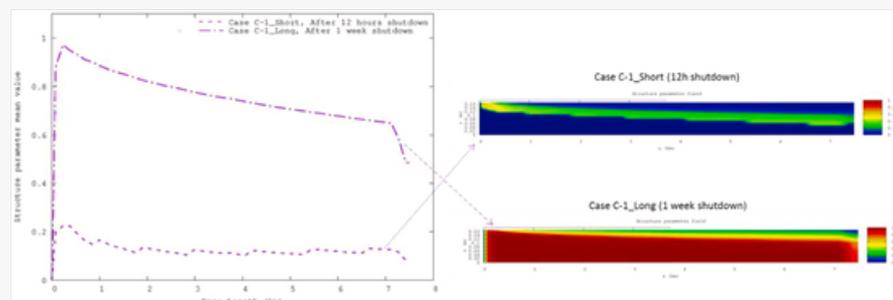
Using  $\lambda_0$  correlation (Eq. 8) in StarWaCS, we are now able to calculate the initial state of the structure parameter  $\lambda_0$  for the four different shutdown scenarios defined in Table 3.

We present in the left of Fig. 18, the mean structure parameter profile along the pipeline and the 2D axisymmetric structure parameter field after different shutdown periods for Case C-1. First, obviously, if the shutdown time increases, the temperature in the pipeline decreases, and so the structure parameter increases accordingly. Since the structure parameter represents the gel strength, the longer the shutdown period, the stronger the gel. After a week of shutdown, the temperature being constant and equal to the seabed temperature (cf. Fig. 10), we obtain the strongest gel for the Case C-1 conditions since most of the pipeline has undergone a static cooling.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 18

**Figure 18**



Mean structure parameter profile (left) and 2D axisymmetric structure parameter field (right) along the pipeline after different shutdown times (Cases C-1,  $Q_v = 3500$  bbl/day,  $T_{SeaBed} = 20$  °C).

Thanks to the 2D axisymmetric structure parameter field displayed in the right part of Fig. 18, we observe that the gel strength in the pipeline is heterogeneous. In particular, the gel is weaker close to the wall (blue regions of Fig. 18). Indeed, as shown in Fig. 10, the temperature of the fluid close to the wall is low at steady state, meaning that in this region the fluid has been cooled under flowing conditions (i.e. dynamic cooling). Since a gel formed under dynamic conditions is weaker than a gel formed under static conditions, the gel formed closer to the wall is weaker. The region where the fluid undergoes a dynamic cooling, exhibits low structure parameters values, and occupies almost half the radius of the pipeline at the outlet.

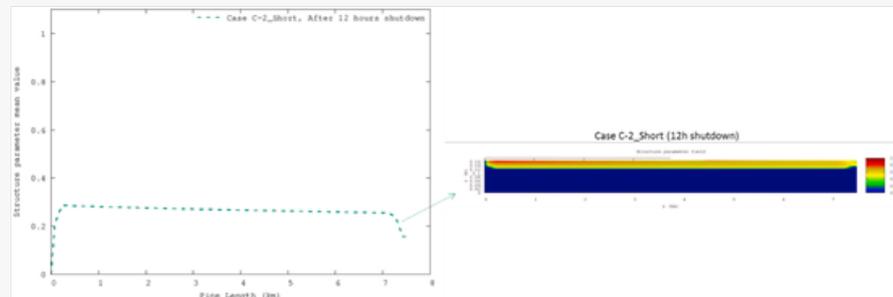
The benefits of this approach is that it includes an integrated mechanical and thermal history of the gel formation and as a result predicts the spatial variations of the gel structure in the pipeline.

Fig. 19 presented the mean structure parameter profile along the pipeline and the structure parameter field after a 12 h shutdown for Case C-3, where the flow rate has been increased to 25,000 bbl/day during the steady state. The flow rate imposed during the steady state conditions has a significant impact on the structure parameter field. Indeed, increasing the flow rate modifies the regions of the pipeline where the fluid undergoes a dynamic cooling and modifies the strong gel regions distribution accordingly. In particular, the temperature of the fluid closer to the wall is higher than for Case C-1 (as observed in Figs. 10 and 11) and so the gel close to the wall undergoes a static cooling instead of a dynamic cooling. As a results, increasing the flow rate makes the low structure parameter region near the wall disappear and leads to the formation of a strong gel layer stuck at the wall as illustrated in Figure 19.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 19

**Figure 19**



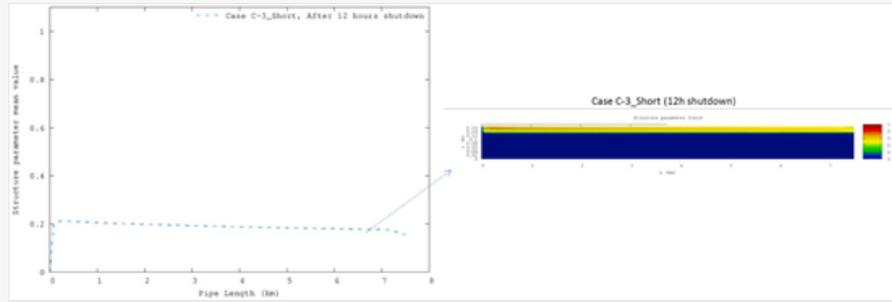
Mean structure parameter profile (left) and 2D axisymmetric structure parameter field (right) along the pipeline after a 12h shutdown time (Case C-2,  $Q_v = 25,000$  bbl/day,  $T_{\text{SeaBed}} = 20$  °C).

We present in Fig. 20 the mean structure parameter profile along the pipeline and the structure parameter field after a 12h shutdown for Case C-3, where the external temperature ( $T_{\text{SeaBed}} = 25$  °C) is larger than in Case C-2. The increase of  $T_{\text{SeaBed}}$  does not modify the structure field pattern since a stronger gel layer at the wall remains. However, the increase of  $T_{\text{SeaBed}}$  makes the mean structure parameter decrease from about 0.26 to 0.18.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 20

**Figure 20**



Mean structure parameter profile (left) and 2D axisymmetric structure parameter field (right) along the pipeline after a 12h shutdown time (Case C-3,  $Q_v = 25,000$  bbl/day,  $T_{\text{SeaBed}} = 25$  °C).

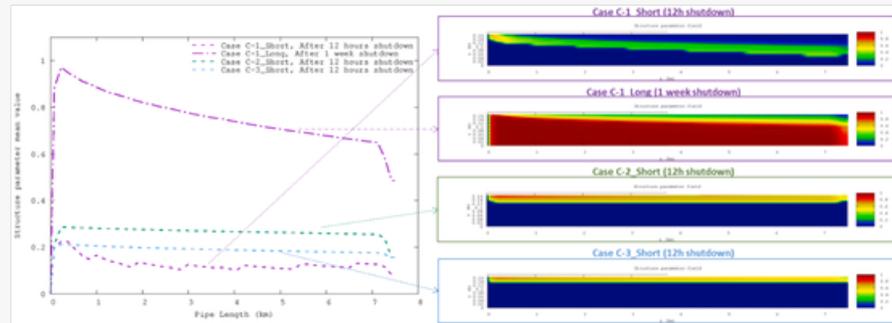
In Fig. 21, we sum-up all the results in terms of mean structure parameter profiles and 2D axisymmetric structure parameter fields. We can draw the following conclusions:

- A larger shutdown time leads to a stronger gel structure occupying a larger region of the pipeline,
- After a 12 h shutdown, a larger external temperature leads to a weaker gel structure in average,
- A larger flow rate imposed during the steady state does not foster any dynamic cooling close to the wall and leads to a stronger gel structure in average ( $\lambda_0$  (Case C-1\_Short)  $<$   $\lambda_0$  (Case C-2\_Short)).

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 21

Figure 21



Mean structure parameter profile (left) and 2D axisymmetric structure parameter field (right) at initial state in the pipeline after different cooling conditions (Cases C-1, C-2 and C-3).

## 5 Restart pressure predictions for different cooling conditions

StarWaCS software is used to simulate and present the whole restart process given the four initial states of the gelled waxy crude oil established in Section 4.3. StarWaCS can simulate the restart of a weakly compressible viscoplastic and thixotropic fluid flushed by another fluid. We suppose that the incoming fluid is a Herschel-Bulkley fluid with the parameters determined in Section 3.1 at a temperature  $T_{\text{inlet}} = 70$ °C (i.e.  $k = 0.0035$  Pa s,  $\tau_{y0} = 0$  Pa and  $n = 1$ ). The outgoing fluid is a Houska fluid based on the parameters determined in Section 3.3.

A pressure ramp of 50 bar/h is imposed at the pipe inlet and by checking above which pressure the flow restarts (as soon as the mean fluid velocity is larger than  $10^{-4}$  m.s<sup>-1</sup>), a fair estimation of the restart pressure is done. We present in this section the restart pressure predictions for the four different shutdown scenarios.

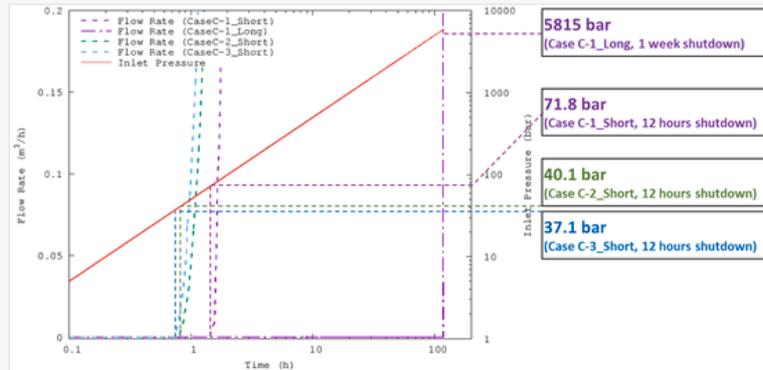
We plot in Fig. 22 the time evolution of flow rates and inlet pressures during the restart process for all the cases. The restart pressure  $P_{\text{Restart}}$  is given for each case on the right side of Fig. 22. The restart pressure lies in the range of values between 37.1 bar and 5815 bar, depending on the different conditions imposed during the cooling process. This

reinforce the fact that a fair description of the gel at the initial state is a key point since the initial state have a tremendous impact on the restart pressure.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 22

**Figure 22**



Time evolution of flow rates and inlet pressures during the restart of a gelled waxy crude oil pipeline for different initial states.

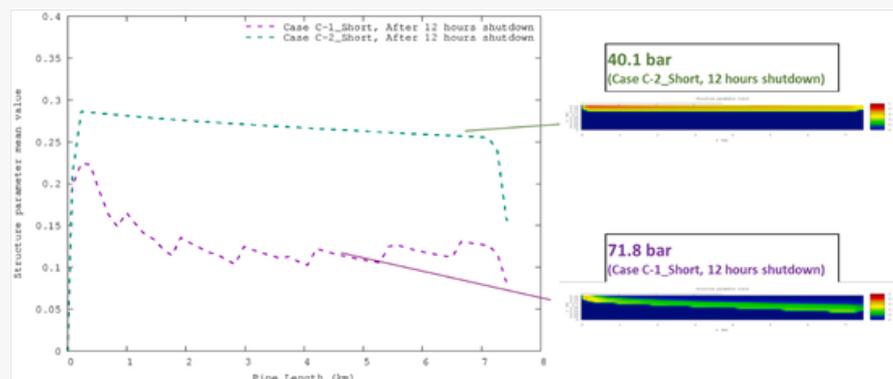
We observe that an increase of the external temperature and/or the flow rate leads to decrease by 50% the restart pressure. Also, after a 1-week shutdown, the restart pressure is dramatically increased until overpassing 5800 bar when  $T_{SeaBed} = 20^{\circ}C$ .

We would like to comment the counterintuitive observation illustrated in Fig. 23. Previously, we showed that increasing the flow rate during the steady state leads to the rise of the structure parameter in average ( $\lambda_0$  (Case C-1\_Short)  $<$   $\lambda_0$  (Case C-2\_Short)). Though the mean structure parameter profile increases with increasing flow rate, the restart pressure is lower for the larger flow rate case  $P_{Restart}$  (Case C-1\_Short)  $>$   $P_{Restart}$  (Case C-2\_Short). The explanation for this apparent contradiction is that an average characterization of the gel strength is not enough to predict restart pressure. In other words, a larger structure parameter on average doesn't mean necessarily a larger restart pressure. In particular, the shape and the location of the gel region at the initial state both influence the pressure required to restart the flow.

 Images are optimised for fast web viewing. Click on the image to view the original version.

alt-text: Figure 23

**Figure 23**



Mean structure parameter and 2D structure parameter field after a 12h shutdown (Case C-1\_Short and Case C-2\_Short): impact of the flow rate  $Q_v$  on the restart pressure  $P_{Restart}$ .

From Fig. 23, we can assess roughly the flowing cross section, i.e. the corresponding flowing diameter,  $D_f$ . By increasing the flow rate (Case C-2\_Short), a stronger gel layer is formed close to the wall that leads to a larger flowing cross section ( $D_f(\text{Case C-2_Short}) \approx 0.24$  m) than for the lower flow rate case (Case C-1\_Short) where a weaker gel band occupies a large part of the pipeline cross section; so for Case C-1\_Short, we have a flowing cross section of about  $D_f(\text{Case C-1_Short}) \approx 0.12$  m.

From the conservative law defined by Eq. 9 and assuming that the restart pressure is mainly supported by the restart of the fluid part only (where  $\lambda = 0$  across the pipeline section), we get  $P_{\text{Restart\_Conservative}}(\text{Case C-1\_Short}) \approx 67.5$  bar  $>$   $P_{\text{Restart\_Conservative}}(\text{Case C-2\_Short}) \approx 33.7$  bar for Case C-1\_Short and Case C-2\_Short respectively. We thus obviously see that by decreasing the flowing cross section, the restart pressure is increased.

$$P_{\text{Restart\_Conservative}} = \frac{4(\tau_{y0} + \lambda\tau_{y1}) \times L}{D} \quad \text{Eq. 9}$$

The minimum restart pressure values required to restart a gelled Malaysian waxy crude oil pipeline for different initial states are gathered in Table 7. We compare the restart pressure computed with StarWaCS and the values of pressure obtained from the Conservative Law (Eq. 9). As observed in Section 4.3, the gel has a heterogeneous structure and the corresponding structure parameter field exhibits a large spatial variation all over the pipeline. Moreover, since a single mean value of the structure parameter  $\lambda$  (referenced as  $\lambda_{0\_Mean}$  in Table 7, and corresponds to the  $\lambda$  value averaged over the entire pipeline) is used in Conservative Law (Eq. 9), the conservative restart pressure is dramatically overestimated compared to the StarWaCS predictions.

alt-text: Table 7

Table 7

 The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

Mean structure parameter values and minimum restart pressure values for a Malaysian waxy crude oil pipeline calculated using StarWaCS or the Conservative Law, after different cooling conditions.

Initial state features	Cases	Initial mean structure parameter ( $\lambda_{0\_Mean}$ )	Restart Pressure calculated from	
			StarWaCS-1.5D	Conservative Law
	Case C-1_Short	0.12	71.5 bar	2,311 bar
	Case C-1_Short ( $\chi_T = 0$ )	0.12	71.8 bar	2,311 bar
	Case C-1_Long	0.74	5,815 bar	14,126 bar
	Case C-2_Short	0.26	40.0 bar	4,979 bar
	Case C-3_Short	0.18	37.1 bar	3,454 bar

As displayed in Table 7, we also assessed the influence of the compressibility coefficient  $\chi_T$  on the restart pressure for Cases C-1. Using StarWaCS, we calculated the restart pressure for Case C-1\_Short when the compressibility coefficient is set to 0 ( $\chi_T = 0$ ). We observed that the compressibility has negligible impact on the restart pressure for this specific Malaysian waxy crude oil pipeline.

## 6 Conclusions

We presented in this paper an original methodology that able to consider the impact of the shutdown scenario on the structure of a gelled waxy crude oil. Restart pressure predictions have been conducted for four different shutdown conditions by applying an original methodology to assess the initial gel structure. Different operating conditions (i.e. ambient temperature and flow rate) yields to different cooling processes, hence, leads to different minimum restart

pressure. The results clearly showed that waxy crude oil gel exhibits heterogeneous gel structure along the pipeline which dictates the restart pressure.

We noticed that obviously when the shutdown time is increased, the restart pressure ( $P_{\text{Restart}}$ ) increased. After a shutdown period of 1 week, the restart pressure rises to very huge values larger than 5000 bar. We also observed that increasing the flow rate ( $Q_v$ ) and the external temperature ( $T_{\text{SeaBed}}$ ) leads to decrease of restart pressure ( $P_{\text{Restart}}$ ) by a factor 2. We also conclude that the assumption of homogeneous gel structure along the pipeline is not valid. Finally, the use of an average initial structural parameter value to calculate the restart pressure using Conservative Law leads to dramatic overestimation of the restart pressure.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

**Q3** The authors would like to thank PETRONAS Research Sdn. Bhd. for the funding of this research project as well as [IFPEN](#) for leading and carrying out the research activities.

## References

 The corrections made in this section will be reviewed and approved by a journal production editor. The newly added/removed references and its citations will be reordered and rearranged by the production team.

Ajienka, J.A., Ikoku, C.U., 1995. Criteria for the design of waxy crude oil pipelines: maximum pump (horsepower) pressure requirement. *J. Petrol. Sci. Eng.* 13, 87–94.

Chala, G.T., Sulaiman, S.A., Japper-Jaafar, A., Wan Abdullah, W.A.K., Mior Mokhtar, M.M., 2014. Gas void formation in statically cooled waxy crude oil. *Int. J. Therm. Sci.* 86, 41–47.

Chala, G., T, S., Sulaiman, A., Japper-Jaafar, A., 2018. Flow start-up and transportation of waxy crude oil in pipelines-A review. *J. Non-Newtonian Fluid Mech.* 251, 69–87.

Davidson, M., R, Q., Nguyen, D., Chang, C., Ronningsen, H., P., 2004. A model for restart of a pipeline with compressible gelled waxy crude oil. *J. Non-Newtonian Fluid Mech.* 123, 269–280.

Houska, M., 1981. Engineering Aspects of of the Rheology of Thixotropic Liquids Ph.D. thesis, Faculty of Mechanical Engineering Czech Technical University of Prague-CVUT, Prague.

Lin, M., Li, C., Yang, F., Ma, Y., 2011. Isothermal structure development of Qinghai waxy crude oil after static and dynamic cooling. *J. Petrol. Sci. Eng.* 77, 351–358.

Mendes, P., R, S., 2009. Modeling the thixotropic behavior of structured fluids. *J. Non-Newtonian Fluid Mech.* 164, 66–75.

Mendes, P., R, S., F, S., Soares, A., Ziglio, C., M., Gonçalves, M., 2012. Startup flow of gelled crudes in pipelines. *J. Non-Newtonian Fluid Mech.* 23–31.

Sestak, J., Charles, M.E., Cawkwell, M.G., Houska, M., 1987. Start-up of gelled crude oil pipelines. *J. Pipelines* 15–24.

Sierra, A., G. P., Vargas, R., Ribeiro, S., S., 2016. Startup flow of elastoviscoplastic thixotropic materials in pipes. *J. Petrol. Sci. Eng.* 147, 427–434.

Vinay, G., 2005. Modélisation du redémarrage des écoulements de bruts paraffiniques dans les Ph.D. thesis École des Mines de Paris, Paris.

Vinay, G., Wachs, A., Frigaard, I., 2009. Start-up of gelled waxy crude oil pipelines: a new analytical relation to predict the restart pressure. In: *SPE Asia Pacific Oil and Gas Conference and Exhibition*. SPE, Jakarta.

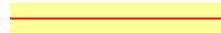
Vinay, G., Hénaut, I., Cassar, et C., 2011. Méthode de redémarrage des écoulements de bruts paraffiniques. France Brevet 1101878.

Wachs, A., Bruy, F., Henaut, A., 14 October 2008. Method of Determining Paraffinic Crude Flow Restart Conditions. United States of America Patent US007437247B2.

Wachs, A., Vinay, G., Frigaard, I., 2009. 1.5D numerical model for the start up of weakly compressible flow of a viscoplastic and thixotropic fluid in pipelines. *J. Non-Newtonian Fluid Mech.* 159, 81–94.

---

•



•

---

