Denise Diniz Souto Lima

**Startup Flow of Gelled Crudes
after a Shutdown: Comparison between
Simulations and Experimental Data**

DISSERTAÇÃO DE MESTRADO

Dissertation presented to the Programa de Pós-Graduação em Engenharia Mecânica of the Departamento de Engenharia Mecânica do Centro Técnico Científico da PUC-Rio, as partial fulfillment of the requirements for the degree of Mestre em Engenharia Mecânica.

Advisor: Prof. Paulo Roberto de Souza Mendes

Rio de Janeiro
April 2015

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To passion.
Without it, life would make no sense.

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Abstract

Lima, Denise Diniz Souto; Mendes, Paulo Roberto de Souza (Advisor). **Startup Flow of Gelled Crudes after a Shutdown: Comparison between Simulations and Experimental Data.** Rio de Janeiro, 2014. 154p. MSc. Dissertation - Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

The main concern regarding to the restart operations for production wells in oil & gas systems is the forecast of minimum pressure needed to overcome the gel strength, i.e. the pressure which generates a wall stress higher than the yield stress of the gelled oil. The petroleum accumulations around the world have raised big issues regarding flow assurance aspects, especially in some ultra-deep water scenarios. In these cases, when the oil presents unusual high values for the Wax Appearance Temperature (WAT) and even for the yield stress, the flow restart procedure can be an issue, after shutdown times of the oil production. Usually, the thixotropic models applied for start-up flow are defined by a *Bingham*-like stress equation whose yield stress depends on a structure parameter (λ), following *Houska* assumptions. This parameter is a non-negative scalar number that represents the structuring level of the material inside the pipeline. The structure parameter is governed by an evolution equation that considers a build-up term and a breakdown term. The main objective of this work is to evaluate the relationship between the parameters of the constitutive equations for *Houska* and *SMT* models (dimensionless coefficients of the evolution equations for the structure parameter) and the representativeness of the simulation results obtained by these models, regarding times for the production stabilization after a restart, delay times and yield stresses, when compared to experimental data.

Keywords

Restart; simulation; experimental data; yield stress; gelification; structuring; build-up term; breakdown term.

Resumo

Lima, Denise Diniz Souto; Mendes, Paulo Roberto de Souza. **Reinício de Escoamento de Óleos Gelificados após Parada de Produção: Comparação entre Simulações e Dados Experimentais**. Rio de Janeiro, 2014. 154p. Dissertação de Mestrado - Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Uma preocupação constante referente às operações de reinício de escoamento em poços produtores de óleo é a previsibilidade da mínima pressão necessária para iniciar o fluxo após uma parada de produção. Tal pressão se refere àquela que promove tensões de cisalhamento junto à parede do duto que superam o valor da tensão limite de escoamento do referido fluido. A necessidade de desenvolvimento de diferentes tipos de campos de petróleo ao redor do mundo tem promovido discussões sobre importantes aspectos de garantia de escoamento dos fluidos, especialmente em cenários de produção em águas ultra-profundas. Nesses casos, quando o fluido apresenta valores elevados para a temperatura mínima de aparecimento de cristais (TIAC) ou ainda para a tensão limite de escoamento, o procedimento de repartida de poço após uma parada de produção pode representar um problema. Em geral, os modelos tixotrópicos utilizados na avaliação de reinício do escoamento são definidos por uma equação constitutiva baseada no modelo de *Bingham*, na qual a tensão de cisalhamento depende do grau de estruturação do fluido no interior do duto, representado por um parâmetro adimensional positivo (λ). A evolução deste parâmetro no tempo é governada por uma equação constitutiva que considera um termo de construção e um termo de quebra do gel. Este trabalho tem como principal objetivo avaliar o comportamento do reinício da produção através da variação destes parâmetros/termos segundo modelos tixotrópicos específicos (*Houska* e *SMT*) e a representatividade dos resultados de simulação quando comparados aos dados experimentais.

Palavras-chave

Repartida de escoamento; simulação; dados experimentais; tensão limite; gelificação; estruturação; termo de construção; termo de quebra.

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Nomenclature

A	Cross section área of pipeline (m^2)
c	Mass fraction of fluid
D	Internal diameter of pipeline (m)
D, d	Strain rate tensor
f	Friction factor
G'	Elastic modulus
G''	Viscous modulus
GOR	Gas-Oil ratio
H-B	Herschell-Buckley
IFP	Institut Français du Pétrole
JIP	Joint industry project
K	Flow consistency index
k	Positive scalar Lagrangian parameter
L	Flowline length (m)
n	Flow behavior index
p	Pressure (psi)
p_{entry}	Pressure at inlet flowline
p_{outlet}	Pressure at outlet flowline
r	Internal radius of the flowline
Re	Reynolds number
SI	International unity system
SMT	Souza-Mendes-Thompson
T	Fluid temperature ($^{\circ}C$)
T_d	Delay time (s)
T_s	Stabilization time (s)
u	Velocity vector
U_{ws}	Water superficial velocity
U_m	Mixture velocity
U_o	Mean velocity in orifice
w	Velocity of the fluid, radial or axial (m/s)
$\bar{w}$	Mean velocity of the flow (axial)
WAT	Wax appearance temperature ($^{\circ}C$)
z	Axial position along the flowline (m)
Δp	Pressure drop along the flowline

μ	Dynamic viscosity
μ_a	Apparent viscosity of the fluid (cP)
μ_p	Plastic viscosity of the fluid
ρ_o	Oil density (Kg/m ³)
τ	Shear stress
τ	Extra-stress tensor
τ_y	Yield stress (Pa)
τ_{y0}	Steady-state yield stress (Pa)
τ_{y1}	Thixotropic yield stress (Pa)
$\dot{\gamma}$	Shear rate (s ⁻¹)
Λ	Representation of angle (°)
χ_T	Isothermal compressibility coefficient
Ω_p	Representation of p -centered control volume

1

Introduction

The petroleum accumulations around the world have raised big issues regarding flow assurance aspects, especially in some ultra-deep water scenarios. In these scenarios, the oil has presented, simultaneously, higher Gas-Oil ratio (GOR), long flexible pipelines and low temperatures for reservoirs, features that favor the quick achievement of low temperatures of the produced fluids inside the pipelines, at shutdown events (interruption of oil production). Under this circumstance, the waxy oil cooling promotes a gelation of the fluid that is at rest.

Moreover, the observed high values for the Wax Appearance Temperature (WAT), that is the temperature below which the first wax crystals start to appear at the fluid matrix increasing its viscosity, and also higher values for the yield stress (minimum value that allows the beginning of the fluid displacement, after a shutdown) must be seen as important issues, involving restart problem. The usual solution for the displacement of this structured (gelified) gel is the pumping of another fluid (typically water, diesel or dead oil) into the pipeline at high pressure.

In this context, the gelification phenomenon complicates the operation and design of a pipeline system, due to the necessity of understanding and modeling the complex mechanical behavior of the gelled waxy crudes [1] [2], in order to allow the application of appropriate mitigation practices to avoid flow assurance problems.

The main concern regarding to restart operations of the oil production system is the minimum pressure needed to overcome the gel strength, i.e. that pressure which generates wall stresses higher than the yield stress of the oil. On the literature, the constitutive models used to describe the mechanical behavior of the oil usually ignore time-dependent effects and it is common to consider friction factor correlations restricted to the *Bingham* model to infer the relationship between the flow rate and the pressure drop [3].

Another fundamental concept involving restart concerns is the thixotropy, a phenomenon that talks about the viscosity reduction along the time under the application of a constant shear rate (or a constant shear stress) and its recovering after the stop of the additional energy.

Usually, the thixotropic models applied for start-up flow are defined by a *Bingham*-like stress equation whose yield stress depends on a structure parameter (λ), following *Houska* assumptions. This parameter is a non-negative scalar number that represents the level of the structured material inside the pipeline, which is governed by an evolution equation for unstructuring of the gel along the time under an initial pressure or shear rate application, that considers a build-up term (structuring) and a breakdown term (unstructuring).

Although the compressibility effects may have some importance in the restart flow problem, they are not being considered for the purpose of this work. The reason is the nature of the fluids used for the obtained experimental data, which are incompressible (the same rheology for the incoming and outgoing fluid).

In this context, two thixotropic models developed to emulate restart problem are detailed in later sections: *Houska* and *Souza Mendes/Thompson* (*SMT*). Both models are implemented in StarWaCS software, which was chosen to perform all the simulations that are the focus of this work.

The main objective here is to evaluate the relationship between the parameters variation of the constitutive equations for *Houska* and *SMT* models (dimensionless values b , m and the characteristic time t_{eq} , to be detailed forward) and the representativeness of the simulation results obtained by these models, when compared to the experimental data (measured), regarding to times for the production stabilization from the beginning of restart, delay times (elapsed time between the pressure application and the beginning of the flow) and yield stresses.

Based on this evaluation, an inverse problem is identified and a proposal is done, in order to determine the parameters of constitutive equation for λ evolution, in both models analyzed (*Houska* – b , m - and *SMT* – b , t_{eq}). This proposal consists in the evaluation of the initial necessary data to perform experiments in laboratory, in order to reproduce the flow restart behaviors (assuming determined boundary conditions and a minimum quantity of data to ensure the repeatability of the experiments), which will be used as input in the simulator to calibrate the parameters mentioned above. The complexity involved and spent time to obtain experimentally the parameters of constitutive equations

for λ evolution and the absence of a standard experimental protocol to do it were the main reasons that motivated this proposal.

In the experiments mentioned in this work [32], it were obtained measurements for velocity profiles, inlet pressures and outlet flowrates, which will be timely detailed.

2 Literature review

2.1. Rheology and yield stress issues

Especially for ultra-deep water scenarios, depending on the fluid properties and flow conditions, oil gelification in the production lines may be a big issue, in case of an unplanned shut down, due to the low temperatures.

This gel has some features that leads to a similar behavior comparing to a solid, namely, deforms elastically when subjected to a low shear stress and starts to flow, subjected to a plastic deformation, only after the application of a mechanic solicitation above a minimum shear stress limit, known as *yield stress*.

To estimate the necessary differential pressure to start to break the totally structured gel, promoting the beginning of the fluid displacement, it is usual to consider a simple force balance, expressed by Eq. (1):

$$\Delta P = (\tau * 4 * L) / D \quad (1)$$

where τ is the measured yield stress; L and D symbols represent, respectively, the length and the diameter of the pipeline.

This formulation assumes that the pipeline is entirely filled with gelled oil, the fluid is incompressible and an instantaneous restart occurs. It has been related that the values obtained using this methodology are very conservative and values 4 or 5 times smaller occur in laboratory test loops and field applications [4]. However, there is no design practices or numerical codes really representative of the phenomenon in the literature (not already proven in the field), so that this conservative estimate persists as a reference. Some aspects may explain the difference between this conservative value and the value observed in the field, such as time effects, strain rates, fluid compressibility and the possibility of slip on the pipeline wall.

For the purpose of the work (to check at the simulator the minimum pressure to promote the beginning of the fluid displacement), this estimate is used as a good reference of the shear stresses observed at the experimental data, due to the existence of only one fluid type (cleaning and displaced fluid) at the

simulation, no gas (compressibility is neglected) and a very simple experimental apparatus.

However, to estimate the yield stress in a right concept way, some concerns must to be taken into account regarding to the rheology effects. In this context, the thixotropy is a fundamental concept to be explored in order to better understand its influence in the yield stress forecast.

Barnes [5] published a detailed review of thixotropy, where the phenomenon was described, being discussed several examples, where the thixotropy history was summarized and the state of the art on the subject was presented. Barnes [5] pointed out that most of the available theories only describe the viscous thixotropic phenomenon and only a few attempted to describe viscoelastic effects. The viscous theories were grouped by three categories:

- 1) those that employ the so-called structure parameter, usually represented by the greek letter λ , a scalar quantity that typically varies in the interval $[0,1]$ and represents an indirect measure of the level of structuring (these are usually called *structural kinetics* models);
- 2) those that use some direct information of the microstructure, usually called *microstructural* models; and
- 3) those just based on viscosity-time data.

Another study that also promoted a thorough discussion regarding to what exists about thixotropy on the literature was Mujumdar *et al* [6]. It included a quite complete comparison between the various structural kinetics models then found in the literature. These models consist essentially of an evolution equation for the structure parameter and an algebraic constitutive equation that relates the stress (or viscosity) to the structure parameter.

The constitutive equation that makes part of the structural kinetics models usually comprises three additive terms: one for the yield stress (normally taken as structure-parameter-dependent); one involving a structure-parameter-dependent viscosity (the so-called structural viscosity) and that one involving the viscosity of the completely unstructured fluid. In most models, both first and second terms are assumed, for simplicity, to depend linearly on the structure parameter. In some

recent models, a maximum elastic strain is included in the yield stress term, rendering it the capability of predicting elastic effects [7].

Regarding to evolution equation for the structure parameter, it has a physical understanding when it is considered two main terms to describe the structure parameter behavior: a structuring term and an unstructuring term. On the other hand, the parameters that are used to govern the evolution of each term are obtained, for each different model, based on experimental data adjustments.

Mewis & Wagner [8] detailed the fundamentals of thixotropy, with a particularly elucidative explanation on the difference between thixotropy and viscoelastic behavior, pointing out the incapability of the existing viscoelastic thixotropic models available in the literature, based on the Maxwell model, in predict what distinguishes experimentally thixotropy from viscoelasticity, namely an instantaneous drop in shear stress when the shear rate is suddenly decreased. Another important issue is the limitation of the presently available Maxwell-type viscoelastic models due to the absence of yield stress in the model predictions.

In short, a unified treatment about thixotropy is still lacking, due to intricacy of the subject. Assumptions adopted for simplicity reasons and not based on physical arguments are common at many of the models available in the literature, making them limited in terms of predictive capability.

2.1.1.

Experimental methods for yield stress determination

There are some rheometric methods using small amounts of sample that are able to determine the yield stress, an important physical property experimentally obtained to describe the gelled fluids flows. This parameter represents the mechanical strength of the paraffinic gel.

Meanwhile, the values obtained in each method can be different, what could be explained by the way that the forces are applied on the sample during the experiment. Besides that, each methodology evaluates a different stage of the gel breaking process.

Another issue is that the measurement of the yield stress requires special attention to the time variable, since the fluid cannot flow immediately during the

application of the stress for a short time, but it can occur when it is considered for a longer period of time.

Below are presented the main tests performed at laboratories of fluid mechanics, regarding yield stress measurements:

- **Creep & Recovery Flow Test** – the sample is submitted to a shear stress, which is maintained constant during a specified period, being the fluid observed regarding to its strain behavior (if there is or not a stabilization tendency of it along the time). With this test, it is possible to obtain the dynamic yield stress (when the pre-shearing is applied to the sample before the test), the static yield stress (when the pre-shearing is not applied) and the flow curve (steady state conditions for different strain rates).

- **Strain Sweep Test** – oscillatory test during which a fixed frequency is maintained, where the response is measured in terms of amplitude and phase, for the changes in the amplitude of the cosine function imposed. From the output variables is possible to calculate the values for the elastic modulus (G') and the viscous modulus (G'').

- **Frequency Sweep Test** – oscillatory test during which a fixed amplitude is maintained, where the response is measured in terms of amplitude and phase, for the changes in the frequency of the cosine function imposed. From the output variables is possible to calculate the values for the elastic modulus (G') and the viscous modulus (G'').

The oscillatory rheometry allows the characterization of the mechanical behavior for a viscoelastic material through two parameters: the elastic modulus (G') and the viscous modulus (G''). The second one is much more significant when the mechanical behavior for non-structured fluids is being described, presenting, the first one, negligible values in this case.

In case of structured fluids like paraffinic gels, both modules are measurable and the predominance of each one will be dependent of the structuration level and the external perturbation imposed to the sample during the rheological measurement.

At low shear stresses, the gelled fluids present higher values for G' than for G'' , denoting the dominant character of a solid material. However, this behavior is modified when a critical shear stress is applied and the fluid starts to behave as a liquid.

In the literature, the yield stress that represents the solid-liquid transition of the structured material is determined experimentally by the intersection between the elastic modulus and the viscous modulus curves (Figure 1).

However, this procedure is not physically representative of this phenomenon (identification of yield stress), considering that the elastic and the viscous modules, per definition, do not vary with the increment of shear rate, for shear rate values under the value associated to the yield stress. In these situations, the fluid is totally structured. The more suitable procedure to obtain the 'apparent' yield stress is the Creep Flow Test, described above.

Figure 1 – Example of the experimental method to determinate the yield stress using G' and G''

2.1.2. Constitutive models considering thixotropy

Many authors have developed numerical solutions for several types of flow based on the knowledge about the rheological behavior of thixotropic fluids.

Ritter & Batycky [9] were responsible for the first report considering the numerical prediction of a thixotropic fluid flow. They realized the importance of

temporal dependency on the rheological properties to predict pressures and velocities fields at the restart flows of paraffinic fluids. Their perception at that time was that the existent thixotropic models were complex and inappropriate, being used, in this way, the interpolation of rheological data obtained experimentally (equilibrium curves for different shearing times and shear stress behavior in restart tests). The yield stress was omitted in this work.

A model more complete, taking into account the yield stress, to determine the operation time to remove the gelified material inside the pipeline, after a shutdown, was proposed by Sestak *et al* [10]. In this problem, a *Newtonian* fluid was used to push the thixotropic material, both fluids being incompressible. The inertial effects were also neglected and the interface between the fluids was considered plane. The thixotropic model used was the same proposed by Houska [11] *apud* Mewis & Wagner [8] and the transient term of momentum equation was neglected, considering an instantaneous equilibrium between the pressure and viscous forces. The temporal variation in this model is represented by the changing in the rheological properties while the material is getting fractured.

Chang *et al* [1] developed, in later works, a model similar to the Sestak *et al* [10]. The compressibility of the material was neglected and a phenomenological approach was considered, based on previous work [2] about different yield stresses. The model was used also by Davidson *et al* [12] to model the restart of a compressible material.

The first model considering simultaneously the fluid compressibility, the transient term and a analysis in two dimensions to simulate the restart flow for a Bingham fluid was that presented by Vinay *et al* [13]. A year after, Vinay *et al* [14] presents another work, comparing a new 1D model with the previous 2D model, showing a good concordance between them. The authors state that the first one is more efficient due to the significant reduction on computational time.

In a later work, Wachs *et al* [15] improved the Vinay *et al* [14] model including a rheological equation, incorporating the thixotropy concept. The model was a mix between 1D and 2D models, naming the new model as 1.5D. The thixotropic model used by Wachs *et al* [15] is a modification of the Houska [11] model *apud* Mewis & Wagner [8] for compressible materials.

The modelling of the experimental data presented in this work was done considering the both models implemented on the StarWaCS (detailed on chapter 3), the software that uses the 1.5D methodology mentioned above and the indirect microstructural approach, which is intuitive and allows the modeling of data with good accuracy.

2.2.

Constitutive equations involving *non-Newtonian* fluids

This type of fluid is known by the relationship between the shear rate and shear stress, which is not linear, considering steady state conditions of flow.

In general, *non-Newtonian* fluids obey the Eq. (2), however the apparent viscosity is not constant, changing with the shear rate.

$$\mu_a = \frac{\tau}{\dot{\gamma}} \quad (2)$$

In Figure 2 is resumed the types of fluids, regarding to the relationship between the shear stress and the shear rate, considering or not the existence of yield stress. These fluid behaviors will be detailed on the following items.

Figure 2 - Fluids behaviors for *non-Newtonian* materials no time-dependent under shearing [16]

2.2.1.

***Bingham* model**

For the fluids represented by this model, is required the application of a minimum shear stress, known as “yield stress”, to promote a shear strain. Below this minimum stress value, this type of fluid behaves like a solid and its displacement is only possible as a plug flow.

The mathematical equation that describes the behavior for *Bingham* fluids is:

$$\tau = \mu_p \dot{\gamma} + \tau_y \quad \text{for } \tau > \tau_y \quad (3)$$

$$\dot{\gamma} = 0 \quad \text{for } \tau \leq \tau_y$$

where the rheological parameters are: μ_p , the plastic viscosity and τ_y , the yield stress. The apparent viscosity for this type of fluid is a function of the shear rate and can be represented by the expression:

$$\mu_a = \mu_p + \frac{\tau_y}{\dot{\gamma}} \quad (4)$$

The term “apparent” has its origin in the fact that this viscosity, when mentioned, must be always associated to a specific shear rate, i.e., this parameter is not a fixed value. The flow and viscosity curves associated to this fluid model are shown in Figure 3.

Figure 3 – Flow and viscosity curves for *Bingham* fluid [16]

Analyzing the Eq. (4), it is observed that for very high shear rates, the apparent viscosity tends to a constant value, which is the plastic viscosity of the *Bingham* model. This parameter has a significant importance for the resistance to the flowing, that is represented by the friction between the dispersed particles and between the molecules themselves of the dispersant liquid [15].

It is known that if the concentration of the dispersed particles increases the plastic viscosity also increases. Meanwhile, the yield stress increases when the forces between particles increases, i.e., when the ionic potential of the medium increases.

An example of fluid that presents behavior according to the *Bingham* model are the diluted suspensions of solid in liquids in general. Another particular

examples are the bentonite clay dispersions in water, used as drilling fluid, and some calcite dispersions in water.

2.2.2. Ostwald de Waale model

Also known as power-law fluid model, it is expressed by the following equation:

$$\tau = K * (\dot{\gamma})^n \quad (5)$$

where K is the flow consistency index and n is the flow behavior index. While n is a dimensionless number, K is a physical dimension (Pa.s^n – international unity system – SI).

The physical meaning for the n index is to measure how far from the *Newtonian* behavior ($n = 1$) the fluid is considered. Meanwhile, the K index indicates the degree of resistance of fluid to flow. It can be interpreted as a viscosity measurement, since the equation for *Newtonian* and *non-Newtonian* fluids are similar, except for the n index.

Although this model is not applicable for any type of fluid, even less for all the shear stress range, there are a significant part of the *non-Newtonian* fluids that presents the power model behavior, in a large range of shearing velocities.

Some flow curves that obey the power-law behavior Eq. (5) were shown before, in Figure 2. The fluid represented by n value less than 1 is called *pseudoplastic*. In this case, the viscosity decreases with the increase of the shear rate. For the n value higher than 1 the fluid is called *dilatant*, for which the viscosity increases with the increase of the shear rate. The particular case occurs for the n value equal to 1, when the fluid has a *Newtonian* behavior (continuous rate of increase for the viscosity with the increase of the shear rate).

It is important to observe that power-law fluids don't present a minimum shear stress to start the flow (yield stress). In Figure 2, this behavior is represented by the lower curves of the chart.

The power-law equation in a log-log form is represented by Eq. (6):

$$\log \tau = \log k + n * \log(\dot{\gamma}) \quad (6)$$

If different values for shear stress and its respective shear rate (stabilized) are plotted in a log-log chart, a straight line is obtained, represented by Eq. (6), whose inclination determines the n value, while the K is the value that the flow consistency index assumes when $\log(\dot{\gamma})$ is equal to 0 (i.e. $\dot{\gamma} = 1$, see Figure 4).

Figure 4 – Flow curves for a power-law fluid behavior [16]

Another way to evaluate the behavior of a power-law fluid is through its apparent viscosity. This parameter obeys the following equation, obtained from the combination of the previous Eq. (2) and Eq. (5):

$$\mu_a = k * (\dot{\gamma})^{n-1} \quad (7)$$

According to this equation is easy to see that the dependency of the apparent viscosity in relation to shear stress is decreasing for n value between 0 and 1 and crescent for n value higher than 1, what is shown in Figure 5 below, through a Log-Log chart.

Figure 5 - Viscosity curves for a power-law fluid behavior [16]

The *pseudoplastic* fluids are more common than the *dilatant* ones. Due to their typical behavior, the decrease of the viscosity with the shear rate increment, more quantity of mass can flow for a certain pressure level or less quantity of energy is necessary to maintain a specific flowrate.

Many liquid materials like suspensions, dispersions and emulsions with a great commercial importance have a *pseudoplastic* behavior.

The *pseudoplastic* systems, despite the homogeneous appearance, consist of dispersed particles with irregular shapes. At rest, these materials maintain a certain irregular internal configuration, being characterized by a high resistance against the flow, due to their high viscosity.

When the shear rate is increased, many dispersed align themselves in the flow direction, i. e., in parallel with the direction of the pressure differential. This alignment between particles or molecules facilitates the slip along the flow, reducing the viscosity.

For many liquid materials the behavior mentioned above is reversible, i. e., they recover their original high viscosity, when the shearing is reduced or ceased. Theoretically, the particles return to their natural state of non-oriented interaction in relation to the shearing forces, due to the *Brownian* motion.

Regarding to their rheological behavior, the *pseudoplastic* fluids present three distinct regions with a tendency of constant viscosity. The first one is the region of very low shear rates (see Figure 6), when the fluid has a constant viscosity (η_0), independently on the shear rate, with a behavior similar to a *Newtonian* model. In this region, the *Brownian* motion maintains all the

molecules and/or particles random, ignoring the inertial effects of orientation by shearing. In the intermediate region, the viscosity decreases exponentially, because the shearing forces overcome the Brownian motion forces, from which the shear rate induces the particle (or molecule) orientation. In the last region (higher shear rates), a state of almost perfect orientation occurs and the fluid tends asymptotically to a constant viscosity value again (η_{∞}) [15].

Figure 6 – Viscosity curve for a typical *pseudoplastic* fluid

On the other hand, the dilatant fluids present viscosity behavior crescent with the shear rate increment. This effect is very uncommon, being observed in some concentrated suspensions and pastes.

In this case, the particles are densely packed and the quantity of dispersant (or solvent) is only sufficient to fill the empty spaces between the particles. At low shear rates, the dispersant lubricates the particles surfaces, allowing an easy positional change. So, the fluid has a behavior of a viscous liquid. For higher shear rates, the dispersed particles will occupy more positions in a same time interval, promoting a fast volume increment, being the quantity of dispersant not enough to be distributed between all the dispersed particles, inducing the system to become more viscous.

2.2.3. Herschel-Bulkley model

The equation used to model this type of fluid is similar to that used for a power-law fluid, with exception for the presence of yield stress (τ_o) parameter, being its behavior represented by the following equation:

$$\tau = k * (\dot{\gamma})^n + \tau_o \quad \text{for } \tau > \tau_o \quad (8)$$

$$\dot{\gamma} = 0 \quad \text{for } \tau \leq \tau_o$$

where the rheological parameters are: K , the flow consistency index, n , the flow behavior index and τ_o , the yield stress. The typical flow curve for this fluid is represented in Figure 7.

Figure 7 – Flow curves for a typical H-B fluid behavior [16]

If the H-B equation presented above is plotted in a log-log chart it will correspond to a line represented by:

$$\log(\tau - \tau_o) = \log k + n * \log(\dot{\gamma}) \quad (9)$$

If different values for shear stress ($\tau - \tau_o$) and its respective shear rates are plotted in a log-log chart, a straight line is obtained, represented by Eq. (9), whose inclination determines the n value, while the K is the value that the flow consistency index assumes when $\log(\dot{\gamma})$ is equal to 0 (i.e. $\dot{\gamma} = 1$, see Figure 8).

Figure 8 – Flow curve for a H-B fluid behavior in a Log-Log chart [16]

For the region of shear stresses below the yield stress (very low shear rates), the viscosity tends to infinity, what is illustrated by the Figure 9.

Figure 9 – Viscosity curve for a H-B fluid behavior

A possible way to determine all the parameters of this model consists in:

- 1) estimate the τ_o value by extrapolation through the $\tau \times \dot{\gamma}$ chart, in cartesian coordinates;
- 2) determine the K and n values through the $(\tau - \tau_o) \times \dot{\gamma}$ chart, in logarithmic coordinates.

Observing the H-B formulation it is possible to conclude that the presence of this three rheological parameters (τ_o , K and n) in its equation makes the model more complete than others, that can be considered as particular cases of H-B model.

In literature, “plasticity” is a term quite used to define the behavior of *pseudoplastic* fluids that present yield stress, represented by the Eq. (8). In this context, under the rheological aspect, a *plastic* fluid can be classified as a solid or a liquid. In general, these fluids are dispersions that, at rest, can form a structured network inter-particles (or inter-molecules), due to the Van der Waals forces and/or polar attraction forces, that difficult the positional changes of a volume element, giving to the system a consistency of a semi-solid structure of high viscosity.

When an external force applied is not enough to overcome the equivalent force that maintains the internal structure of the network, it is observed only an elastic deformation in the system. On the other hand, if the applied force is higher than the internal forces of the structure, the network is broken and changes occur on the positions of volume elements, promoting the displacement of the fluid. This minimum stress responsible to the start of the motion is called “yield stress”.

The most common materials that obey the H-B model are the clay dispersions with polymers, widely employed in the petroleum industry. Some examples are the drilling fluids, dental pastes and cement pastes.

2.3. Thixotropy models for restart problem

The thixotropy phenomenon has been studied over the years, due to its inherent complexity.

A recent concept for thixotropy talks about the viscosity reduction along the time under the application of a constant shear rate (or a constant shear stress) and its recovering after the stop of the additional energy.

According to *Bauer & Collings* [17], thixotropy was defined as “the system is considered thixotropic when there is a reversible, isothermal and time-dependent reduction in the magnitude of the rheology properties, due to the application of a constant shearing.”

At the beginning of the studies about the phenomenon, an important conclusion was done by *Schalek & Szegvari* [18]: the transition liquid-gel could be induced not only by temperature changes, but also through the mechanical agitation at a constant temperature. They demonstrated that when some samples were left at rest, it was possible to observe this transition several times, consisting on a reversible process.

Another concept was formulated by *Pryce-Jones* [19] specifying the viscosity as a characteristic parameter, which defines the thixotropy as “an increase of the viscosity at rest and a decrease of the viscosity when the material is subjected to a constant shear stress”. This definition didn’t make any reference to the time dependence for the viscosity, what caused some confusion between this effect and the shear rate dependence (*shear-thinning* effect).

Mewis & Wagner [8] emphasize some aspects that are common to viscoelasticity and thixotropy, such as thinning and histeresys, besides both being dependent on the time and the shear historical. They affirmed that, in fact, the time scales for the *shear-thinning* effect are very small to be significant or even measurable, and it is exactly this feature that distinguishes this phenomenon from thixotropy.

For short times, the structure is not capable to react quickly, being verified an elastic response and, after a period of time, the system continually adjusts itself, when the viscosity effects start to appear. Throughout this process, the shear stress and the shear rate are directly proportional and the breaking of the structure

doesn't occur, i.e., the material recovers its deformation after stimulus suspension. On the other hand, in terms of thixotropy, the structure delays to present response to the shear, however the structure undergoes intense deformations and has a slow recovering [20].

Thereby, the dependence with time occurs through distinct ways for viscoelasticity and thixotropy, being the recovery of the structure the main difference of behavior.

The procedure suggested by Mewis & Wagner [8] for the thixotropy determination consists on the application of decreasing steps for shear stress. Common viscoelastic fluids react to the sudden reduction of the shear rate with a gradual reduction of the shear stress, up to its stabilization at another level. During the transient reduction of the shear stress, the material recovers partially its deformation up the achievement of the new steady state. On the other hand, a thixotropic material perfectly inelastic would react to the sudden reduction of the shear rate with an immediate reduction of the shear stress, followed by a gradual increment, due to the reconstruction of its structure, up to reach a new state of stability.

The thixotropy effect is related to the transition time between two states of microstructure, due to the flow or the recovering. The restructuration mechanism is dominated by internal collisions and Brownian movements, which can occur during the recovering or simultaneously to the shear. The forces associated to Brownian effects are considerably lower than the shearing forces; thus, reconstruction requires times much higher than that needed to the breaking.

Another important aspect that should be evaluated regarding the problem of restart is the interface between the fluid and the pipe wall. The application of a pressure can promote a shearing of the fluid causing a cohesive failure, when it is possible to affirm that the velocity of the fluid on the contact with the wall is null. In this case, all the process is determined by the rheological properties of the material.

However, under certain circumstances it is possible to observe a slip between the fluid and the wall, where occur an adhesive failure. In this case, the phenomenon shall be governed by the frictional forces and surface, instead of by the rheology [23].

There is not so much knowledge about this phenomenon and all models in the literature are based on the theory of no slip (coming from the postulated of the fluid mechanics area), due to its greater reliability. Besides that, this theory deals with higher shearing forces to overcome the static equilibrium (more conservative).

According to the thesis of Lee [24], the cooling rate during the gel formation determines the type of failure: the highest rates promote the appearance of smaller crystals (higher interfacial area), favoring the occurrence of adhesive failures. Following this tendency, the cohesive failures should occur at low rates of cooling (which is observed in subsea pipelines with thermal insulation).

For now, this knowledge still needs greater repeatability of experimental data to confirm some behaviors, being treated with reservations.

Due to the fact that both *Houska* and *SMT* models have been studied on the scope of a JIP between IFP Energies Nouvelles and other companies, being implemented in StarWaCS, these models will be detailed separate and are the focus on the restart analyzes that will be further presented. Moreover, these models represent an evolution of the previous models developed, taking their relevant aspects into account.

2.3.1. **Houska model**

This model implemented a change in the HB model, which considers the yield stress and the viscosity as functions of a structure parameter λ , related to the resistance degree of the gel.

The equation that represents the behavior of this model is presented below:

$$\tau = (\tau_{y0} + \lambda * \tau_{y1}) + (k + \lambda * \Delta k) * (\dot{\gamma})^n \quad (10)$$

where the meaning of the parameters are:

$\tau_{y0} \rightarrow$ steady-state yield stress (no structured gel due to pre-shearing)

$k \rightarrow$ steady-state viscosity (no structured gel due to pre-shearing)

These two parameters above are constant.

$\tau_{y1} \rightarrow$ thixotropic yield stress (function of the parameter λ)

$\Delta k \rightarrow$ thixotropic viscosity (function of the parameter λ)

$n \rightarrow$ shear thinning coefficient (flow behavior index)

The parameter λ represents a measurement of the structural arrangement of the gel and your value varies from 0 (totally unstructured) to 1 (totally structured). The level of structure varies along the time and according to the shear rate, being represented by the following constitutive equation:

$$\frac{d\lambda}{dt} = a * (1 - \lambda) - b * \lambda * (\dot{\gamma})^m \quad (11)$$

where a , b and m are dimensionless parameters of the model.

While the time contributes to the organization of the structure, the shear rate has the opposite effect on the process (greater is the shear rate, lower will be the degree of structure). Both effects are represented on the Eq. (11) by the parameters a (build-up parameter) and b (breakdown parameter).

Therefore, the model takes into account that the necessary shear stress to promote the restart of the flow is variable and will depend on the previous shear rate to which the fluid was subjected during the gelation process, beyond the elapsed time (cooling of the fluid). Thus, the thermo-mechanical history of the flow affects the mechanical strength of the gel, which reaches the maximum value when the fluid is cooled at rest. If the cooling down of the fluid occurs while it is under shearing the structuring of the gel will be lower and the same will happen to the yield stress. In this context, after reached the thermal equalization, the gel resistance tends to increase along the time, if the gel is still at rest.

The eight parameters that make part of the model, as showed in Eq. (10) and Eq. (11), are experimentally measured and used as input data to the *Houska* model on the *StarWaCS*, software chosen to subsidize all the analysis of this work.

2.3.1.1.

Measurement procedures of parameters for *Houska* model

a) Steady-state yield stress (τ_{y0})

This parameter corresponds to the minimum shear stress necessary to restart the flow when the gel is not structured ($\lambda = 0$). To ensure this condition, it

is recommended the intense shearing of the sample previous to the yield stress measurement, submitting the fluid to high shear rates (over 1.000 s^{-1}). The gel is considered completely unstructured when its viscosity remains the same along the time during the shearing. From this moment on, the shear stress is measured for each shear rate applied. It is recommended to vary the shear stress in decreasing order, which can ensure a better non-structuring of the gel during the tests [21].

The steady-state yield stress is obtained from the shear stress x shear rate curve, with the extrapolation for the x axis value equal to 0 (zero). An example is illustrated in Figure 10, being the fluid represented by the H-B model [22], according to Eq. (8).

Figure 10 – Method to obtain the steady-state yield stress - τ_{y0} [21]

b) Steady-state viscosity (k) and flow behavior index (n)

Considering the H-B fluid behavior mentioned in the previous item and the assumption that $\lambda = 0$, the parameters k and n can be obtained from a fit of a straight line on a chart with the axes $\ln(\tau - \tau_0)$ and $\ln(\dot{\gamma})$, following the example of Eq. (9), what is illustrated by the Figure 11.

The inclination of the line corresponds to n value and the y value for $x = 0$ corresponds to $\ln(k)$.

Figure 11 – Method to obtain the parameters k and n [21]

c) Thixotropic yield stress (τ_{yI})

To perform this measure at the laboratory, the fluid is left at rest for a specific period of time, after which a defined shear rate is applied. The observed shear stress will vary along the time (for the same shear rate) and the value of interest is the maximum for each case (each step of shear rate).

An example of this procedure is showed in Figure 12, for a specified case of shear rate (50 s^{-1}).

Figure 12 - Procedure to obtain the maximum shear stress ($\tau_{y0} + \tau_{yI}$) for a defined shear rate [21]

The maximum shear stress obtained for each shear rate, physically, corresponds to the maximum shear stress necessary to restart the flow ($\tau_{y0} + \tau_{yI}$), considering that the gel is, initially, totally structured (sample cooled at rest, with $\lambda = 1$).

Repeating the procedure above for all the shear rates of interest is possible to plot these points (shear rate x maximum shear stress), obtaining a chart as shown in Figure 13. The maximum shear stress corresponding to $(\tau_{y0} + \tau_{y1})$ is obtained making a regression for these points and extrapolating the regressed line for the value of x equal to zero. Knowing the value of τ_{y0} (previous item), the value for τ_{y1} is obtained by subtraction.

Figure 13 – Method to obtain the maximum shear stress $(\tau_{y0} + \tau_{y1})$ [21]

Other forms to obtain the thixotropic yield stress are, after the period of rest:

- ✓ gradual increase of shear rate with concomitant shear stress measurement;
- ✓ application of a very low shear rate, for instance $0,1 \text{ s}^{-1}$, obtaining the peak value for the shear stress;
- ✓ Oscillatory rheology.

d) Thixotropic viscosity (Δk)

This parameter is obtained through the same procedure to obtain the parameter k . The difference is on the initial condition of the gel structure, which should be fully structured ($\lambda = 1$) in this case. The Eq. (12) below describes this condition:

$$\tau = (\tau_{y0} + \tau_{y1}) + (k + \Delta k) * (\dot{\gamma})^n \quad (12)$$

Considering the same logarithmic interpretation done in Eq. (9) for the H-B equation, the Eq. (12) can be represented by:

$$\ln(\tau - \tau_{y0} - \tau_{y1}) = \ln(k + \Delta k) + n * \ln(\dot{\gamma}) \quad (13)$$

The inclination of this line determines the n value while $(k + \Delta k)$ is the value obtained by the intersection between this line and the vertical axis ($\ln(\tau - \tau_{y0} - \tau_{y1})$) in the log-log chart, when $\dot{\gamma}$ is equal to 1 ($\ln(\dot{\gamma}) = 0$). The parameter Δk is obtained from the subtraction of k value, known previously.

e) Kinetic parameters a , b and m

These parameters are related to the kinetic of the gel structuring and their values are obtained by dynamic measurements (oscillatory tests).

In case of steady state flow, the parameter a is null (there is no increase of the gel structuring) and Eq. (11) can be written as:

$$\frac{d\lambda}{dt} = -b * \lambda * (\dot{\gamma})^m \quad (14)$$

Integrating the Eq. (14), we have:

$$\ln(\lambda) = -b * (\dot{\gamma})^m * t \quad (15)$$

Due to the solidification process caused by the wax crystallization, it is considered a good representation for the parameter λ the measurement of the elastic modulus [21].

Therefore, the Eq. (15) becomes:

$$\ln\left(\frac{G'}{G'_o}\right) = -b * (\dot{\gamma})^m * t \quad (16)$$

where G'_o is the initial elastic modulus and G' is the elastic modulus after shearing of the sample for a period of time t .

The experimental procedure to measure the elastic modulus consists in the previous conditioning of the sample (shearing at different rates: 0, 10, 25, 50 and 75 s⁻¹) for 1 minute. After the pre-shearing stage, the elastic modulus is measured, varying the frequency between 1 and 50 Hz (maximum deformation of 0,04 %).

The figure below illustrates the data obtained for the tests:

Figure 14 – Data obtained from the procedure to measure the elastic modulus for different shear rates [21]

Considering, for instance, the measured values for the frequency of 10 Hz, the data can be adjusted to obtain a straight line in a chart with the axes $(-1/t) * \ln(G'/G'_0)$ – vertical – and $\ln(\dot{\gamma})$ – horizontal, based on the Eq. (16), which is presented in Figure 15. The inclination of the line corresponds to m value and the y value for $x = 0$ corresponds to $\ln(b)$.

Figure 15 - Method to obtain the parameters m and $\ln(b)$ [21]

For the coefficient of gel formation, a , a initial cooling of the sample must be done, at the rate of $1\text{ }^{\circ}\text{C} / \text{min}$ with the fluid at rest, from the highest temperature up to the temperature of interest. After this, the sample is strongly sheared for 10 minutes, to totally break the structure of the gel. The fluid is leave at rest after the shearing and every 1 hour the elastic modulus is obtained, varying

the frequency between 1 and 50 Hz (maximum deformation of 0,04 %). A new chart showed in Figure 16 is obtained for these conditions.

Figure 16 - Data obtained from the procedure to measure the elastic modulus for different times at rest [21]

For the condition at rest, the shear rate is equal to 0 (zero). So, the Eq. (11) is simplified for just one term:

$$\frac{d\lambda}{dt} = a * (1 - \lambda) \quad (17)$$

Integrating the Eq. (17) and replacing the parameter λ by the relation involving the elastic modulus, as done in Eq. (16) the equation becomes:

$$\left(\frac{G'}{G'_{sc}} \right) = 1 - \left(1 - \frac{G'_o}{G'_{sc}} \right) * e^{-a*t} \quad (18)$$

where G' is the viscous modulus after the sample remain at rest for a period of time, G'_{sc} is the viscous modulus immediately after the static cooling of the sample (previous to the pre-shearing to the breaking of the gel structure) and G'_o is the viscous modulus immediately after the pre-shearing (rest time equal to 0s).

Rearranging the Eq. (18), the parameter a can be obtained through the inclination of the regressed line, in a chart where the axes are time (x axis) versus $\ln [(G'/G'_{sc} - 1) / (G'_o/G'_{sc} - 1)]$ (y axis), as shown in Figure 17.

Figure 17 – Method to obtain the parameter a [21]

2.3.2.

Souza Mendes-Thompson (SMT) model

This constitutive model for *viscoplastic* thixotropic materials consists basically of two differential equations, one for the stress and other for the structure parameter, a scalar quantity that indicates the structuring level of the microstructure, as mentioned before. In this model, by definition, it ranges from 0 to 1, 0 corresponding to a completely unstructured state and 1 corresponding to a fully structured state. Moreover, λ increases monotonically as the structuring level increases.

It is worth noting that the structure parameter λ is perhaps the simplest way to describe the microstructure state. Nevertheless, it has been proved useful as a tool for representing and accounting for the structuring level of the material's microstructure [5][8].

The thixotropic fluid is assumed to obey the constitutive model, in which the breakdown term of the evolution equation is a function of the shear stress in such a way that the unstructuring is predicted to occur whenever the stress is above the yield stress. Therefore, the correct physics is taken into account in this model [7]. On the other hand, the compressibility effects are not considered.

The proposed approach for this model is capable of predicting the rheology-related features of startup flow, including the “avalanche effect” [25], i.e. situations of no flow for long time periods during the application of the entrance pressure, and the sudden onset of motion after these times.

The differential equation for the shear stress τ has its basis on the mechanical analog shown in Figure 18 below, where $G_s(\lambda)$ is the structural elastic modulus (i.e. the elastic modulus of the microstructure), $\eta_s(\lambda)$ is the structural viscosity, a function that describes the purely viscous response of the microstructure, η_∞ is the viscosity corresponding to the completely unstructured state (i.e. to $\lambda = 0$), i.e. the infinite-shear-rate viscosity, γ_e is the elastic strain of the microstructure when it is submitted to the shear stress τ , γ_v is the viscous strain and γ is the total strain.

This analog corresponds to the Jeffreys constitutive model for viscoelastic liquids, except that, here, both G_s and η_s are assumed to be functions of the structure parameter λ .

Figure 18 – The mechanical analog of the material's behavior [26]

It is interesting to note that, in the limit when $\eta_s \rightarrow \infty$, the analog in Figure 18 becomes a representation of the Kelvin–Voigt constitutive model for viscoelastic solids (with a retardation time equal to η_∞ / G_s), except that G_s depends on λ . Conversely, in the limit when $G_s \rightarrow \infty$ and η_s is finite, the predicted behavior is the one of a purely viscous fluid (whose viscosity is $\eta_v \equiv \eta_s + \eta_\infty$).

Therefore, because G_s and η_s are allowed to vary with the structuring level, this analog encompasses all types of mechanical behavior, ranging from the purely elastic to the purely viscous, and including viscoelastic, *viscoplastic*, and elasto-*viscoplastic* behaviors. This multifaceted mechanical behavior is typical of many colloids as well as other structured materials.

For the purpose of this work, it will be described a simplified version of the thixotropy model proposed by Souza Mendes [7][26], considering an incompressible, one-dimensional, and isothermal flow, in which the elasticity effects are neglected. Considering this, the stress equation reduces to the Generalized *Newtonian* Fluid model:

$$\tau = \eta(\lambda) * (\dot{\gamma}) \quad (19)$$

The τ and $\dot{\gamma}$ parameters are the intensities of the extra-stress τ and the rate-of-deformation $\dot{\gamma}$ tensors. Considering the assumptions of the model for radial and rotational velocities, equal to zero, these tensors can be represented by the Eq. (20).

$$\tau(r, t) = -\tau_{rz}(r, t); \dot{\gamma}(r, t) = -\frac{\partial v_z}{\partial r}(r, t) \quad (20)$$

The viscosity function η is assumed to be a function of the structure parameter only. When $\lambda = 1$, η acquires its maximum value η_o , the so-called zero-shear-rate viscosity. When $\lambda = 0$, η acquires its minimum value η_∞ , the so-called infinite-shear-rate viscosity. The expression proposed for the dependence of η on λ is:

$$\eta(\lambda) = \left(\frac{\eta_o}{\eta_\infty} \right)^\lambda * \eta_\infty \quad (21)$$

The structure parameter λ is, in general, function of both the extra-stress τ and time t , $\lambda = \lambda(\tau, t)$. Particularly in this model, the structuring level is a function of the stress as opposed to the deformation rate, as discussed in [7][26].

Therefore, in principle, $\lambda = \lambda(\tau, t)$ may be reduced to a function of the radial coordinate r and the time t , i.e. $\lambda = \lambda(r, t)$. For steady state flows,

$$\eta_{eq} = \eta(\lambda_{eq}) = \left(\frac{\eta_o}{\eta_\infty} \right)^{\lambda_{eq}} * \eta_\infty \quad (22)$$

where η_{eq} is the steady-state or equilibrium viscosity (given by the material's flow curve) and $\lambda_{eq}(\tau)$ is the value reached by λ in a steady-state flow whose shear stress is τ . By steady-state flow here we mean a flow that is steady in the rheological or Lagrangian sense, i. e. a flow in which the material particles have constant stress and strain rate histories and, hence, the material's structuring level doesn't change with time.

Solving Eq. (21) for λ_{eq} , we obtain:

$$\lambda_{eq}(\tau) = \frac{\ln \eta_{eq}(\tau) - \ln \eta_\infty}{\ln \eta_o - \ln \eta_\infty} \quad (23)$$

The steady-state or equilibrium structure parameter $\lambda_{eq}(\tau)$ is thus determined once the flow curve of the material $\eta_{eq}(\dot{\gamma}_{eq})$ is available.

It is important to observe that $\lambda_{eq}(\tau)$ can also be defined for motions that are not steady (in the Lagrangian sense). Imagine a material particle that, at a given instant of time, is passing by some point in the flow domain. Typically, its past stress history is not constant and, hence, its microstructure is not in equilibrium (i.e. λ is changing with time) [3].

In this case, $\lambda_{eq}(\tau)$ is defined at this point and instant of time as the value of λ that would be reached in a hypothetical steady flow whose stress intensity is the local instantaneous stress τ . In the same way, $\dot{\gamma}_{eq}$ can also be defined for a transient flow as the strain rate that would be observed in a hypothetical steady flow whose stress intensity is the local instantaneous stress τ .

Once we have the material's flow curve $\eta_{eq}(\dot{\gamma}_{eq})$, the value of $\eta_{eq}(\tau)$ for general transient flows is obtained through the solution of:

$$\tau = \eta_{eq}(\dot{\gamma}_{eq}) * \dot{\gamma}_{eq} \quad (24)$$

A convenient expression to represent $\eta_{eq}(\dot{\gamma}_{eq})$ for *viscoplastic* materials is [27][28]:

$$\eta_{eq}(\dot{\gamma}_{eq}) = \left[1 - \exp\left(-\frac{\eta_o * \dot{\gamma}_{eq}}{\tau_o}\right) \right] * \left\{ \frac{\tau_o}{\dot{\gamma}} + k * \dot{\gamma}_{eq}^{n-1} \right\} + \eta_{\infty} \left[1 - \exp\left(-\frac{\eta_{\infty}}{k * \dot{\gamma}_{eq}^{n-1}}\right) \right] \quad (25)$$

where τ_o is the yield stress, K is the consistency index, n is the power-law index, η_o is the zero-shear-rate viscosity and η_{∞} is the infinite-shear-rate viscosity. In Figure 19 is plotted an example for the respective viscosity behavior.

Figure 19 – The viscosity function for *viscoplastic* liquids [28]

The time evolution of the parameter λ is given by the equation [7][26]:

$$\frac{d\lambda}{dt} = \frac{1}{t_{eq}} * \left[(1-\lambda)^a - (1-\lambda_{eq}(\tau))^a * \left(\frac{\lambda}{\lambda_{eq}(\tau)} \right)^b \right] \quad (26)$$

where t_{eq} is the equilibrium time (time for change of the structure parameter), while a and b are positive dimensionless constants.

Mendes [3] used this model to describe the restart flow of two fluids (called the incoming and the displaced fluids) in a tube of radius R and length L . The thixotropic gelled crude oil is the displaced fluid, which is initially filling the whole tube. This fluid is, at time $t = 0$, pushed by the incoming fluid, with a constant pressure imposed at the tube entrance. The interface between the fluids is assumed to be flat and to move with the average bulk velocity $\bar{U}$ of the flow. This assumption is based on the high consistency of the gelled oil and on the fact that $L \gg R$. In Figure 20 is presented the illustrative representation of the problem.

Figure 20 – Schematic of the problem formulation [3]

The scope of interest for the simulation of this problem goes until the interface $z^*(t)$ reach the end of the tube ($z^* = L$). The position of the interface is governed by the following differential equation:

$$\frac{dz^*}{dt} = \bar{U}(t) \quad (27)$$

where t is the time. The initial condition $z^*(0) = 0$ must be obeyed by the Eq. (27).

For simplicity, it is assumed that the pressure at the outlet $P(L,t) = 0$, meaning that the imposed pressure $P_e (= P_{inlet})$ at the entrance of the tube is, actually, the pressure difference observed between these two points. So, the pressure value at the interface $P(z^*(t))$ ranges between zero and P_{inlet} .

Inertial effects are considered in a simplified manner, by treating the flow as quasi-steady. This means that the pressure gradient is uniform throughout each fluid and the shear stress varies linearly with the radial coordinate. Based on these assumptions, the overall force balances in the two fluids are represented by the following equations:

$$\tau_{R,A} = -\frac{R}{2} * \left(-\frac{P(z^*(t))}{L - z^*(t)} + \rho_A * \frac{d\bar{U}}{dt} \right) \quad (28)$$

$$\tau_{R,B} = -\frac{R}{2} * \left(-\frac{P(z^*(t)) - P_e}{z^*(t)} + \rho_B * \frac{d\bar{U}}{dt} \right) \quad (29)$$

where $\tau_{R,A}$ and $\tau_{R,B}$ are, respectively, the wall shear stresses on fluids A and B. Considering that both fluids are incompressible, $d\bar{U}/dt$ is the same for Eq. (28) and Eq. (29).

Both fluids may be assumed to obey this model, which does not exclude the case of practical interest where the incoming fluid is *Newtonian* with viscosity

μ , like water or a light oil, considering that the described model reduces to *Newtonian* case when $\tau_o = 0$, $K = \mu$, $\eta_\infty = 0$, $n = 1$ and $t_{eq} = 0$.

When an entrance pressure $P_{inlet} > P_{crit}$ (pressure associated to the yield stress) is applied, the thixotropic oil microstructure eventually collapses and the onset of flow is observed. It is important to say that, for a long enough tube, a steady flow ($\bar{U} = constant$) is always expected, where the viscosity of the incoming fluid is larger than the infinite-shear-rate viscosity of the outgoing fluid, i.e. $\mu \dot{\gamma}/\tau_o > \eta_\infty \dot{\gamma}/\tau_o$.

Mendes [3] showed that the thixotropic and inertial effects could be captured by his model, which considered the adoption of a low-viscosity and a high-viscosity incoming fluids to observe their particular behaviors during the restart simulations. These results are commented in the next two items.

For none of the cases showed, from the work performed by Mendes [3], the velocity achieved its asymptotic value (steady-state), due to the tube length considered ($L/R = 100$).

Low-viscosity incoming fluids behavior

If the incoming fluid viscosity is small ($\eta_\infty \dot{\gamma}/\tau_o < \mu \dot{\gamma}/\tau_o \ll 1$), it is expected the monotonic increase of the average velocity until eventually reach its asymptotic value. This is so because the flow resistance is predominantly due to the thixotropic material. The structuring level decreases as the velocity increases, and the oil viscosity approaches asymptotically (from above) the viscosity of incoming fluid ($\eta \rightarrow \mu$). There are no further changes with time after the viscosities become equal, and the steady state flow is observed.

Just to illustrate few results of the work mentioned above, for a specific low viscosity condition ($\mu \dot{\gamma}/\tau_o = 0.1$), two relationships were considered between the applied pressure and the minimum pressure necessary to initiate the flow (which is the pressure associated to the yield stress). The first case considered an inlet pressure of 2,5 times the minimum pressure ($P_{inlet} = 2,5 * P_{min}$) and the second case considered a pressure of 10 times the minimum pressure ($P_{inlet} = 10 * P_{min}$). These situations are represented, respectively, by following Figure 21 and Figure 22.

It can be observed the effect of inertia, when the fluids (considering four thixotropic conditions, varying the equilibrium time t_{eq} of the microstructure changes) remain essentially at rest for several time units. Even under the action of stresses significantly above the yield stress, it takes a significant amount of time for the gelled fluid microstructure to collapse and allow the onset of the visible motion. At some critical instant of time, the velocity starts increasing, in some cases reaching high values in a short period of time, reproducing the so-called “avalanche effect” [25]. It is intuitive and observed during the work simulations [3] that the lower is the viscosity, the more steeply the mean velocity increases with time, because the resistance to the acceleration (inertia force) is lower.

In order to evaluate the results obtained in the simulations in a dimensionless view, the yield stress τ_o was considered as the characteristic stress, being the characteristic shear stress ($\dot{\gamma}_1$) defined as:

$$\dot{\gamma}_1 = \left(\frac{\tau_o}{k} \right)^{1/n} \quad (30)$$

In Figure 21, it is interesting to note that, after the onset of flow at $\dot{\gamma}_1 t \approx 30$, the velocity starts to increase at a very low rate, until the occurrence of the sharp increase at $\dot{\gamma}_1 t \approx 150$ (for the curve $\dot{\gamma}_1 t_{eq} = 100$ in the chart). At the first moment, a significant microstructure collapse occurred, which reduced dramatically the viscosity to about $\eta \dot{\gamma}_1 / \tau_o = 18,7$. But this viscosity remains high, so the velocity at this point is still low. However, from the second moment on, the progressive increasing of the velocity promotes further lowering of the structuring level, in a self-feeding process that lowers the viscosity faster and faster.

Figure 21 – Time evolution of mean velocity: thixotropy effect
 $P_{inlet} = 2,5 * P_{min}$ and $\mu\dot{\gamma}_1/\tau_o = 0.1$ [3]

In the case for high inlet pressure (Figure 22), the microstructure breakdown is much faster and after the onset of motion, no time period of slowly velocity variation is observed, in contrast with what is observed for the case of lower inlet pressure (Figure 21).

Figure 22 – Time evolution of mean velocity: thixotropy effect
 $P_{inlet} = 10 * P_{min}$ and $\mu\dot{\gamma}_1/\tau_o = 0.1$ [3]

Another interesting point is the increase of the time for the onset of flow, when t_{eq} is raised. In Figure 21, the onset of flow occurs at $t=0$ when $t_{eq} = 0$ (no

thixotropy). When $\dot{\gamma}_1 t_{eq} = 1$ the thixotropy is negligible and the delay is still not observed before the onset of flow. For $\dot{\gamma}_1 t_{eq} = 10$ the onset of flow only occurs at $\dot{\gamma}_1 t \approx 10$ while for $\dot{\gamma}_1 t_{eq} = 100$ the onset of flow occurs at $\dot{\gamma}_1 t \approx 30$. This relationship between the t_{eq} and the onset of flow is explained by the fact that higher is t_{eq} more the microstructure remains with high viscosity after the beginning of its collapse, slowing the self-feeding process already mentioned above, that promotes the continuous decreasing of the viscosity and, consequently, the increasing of the velocity rates.

For the case of high inlet pressure, it is again observed the immediate onset of flow for the no thixotropy and low thixotropy cases (respectively $t_{eq} = 0$ and $t_{eq} = 1$), but in contrast to the low inlet pressure case, the velocity also climbs immediately because the structuring level reached is much lower (Figure 22). For $\dot{\gamma}_1 t_{eq} = 100$ the onset of flow occurs at $\dot{\gamma}_1 t \approx 10$, a delay obviously lower than the observed for the low inlet pressure.

High-viscosity incoming fluids behavior

When the viscosity of the incoming fluid is of the same order of the characteristic viscosity of the outgoing fluid, i.e. $\mu \dot{\gamma} / \tau_o = 1$ according to the study present by Mendes [3], the flow resistance of the incoming fluid plays an important role. For these cases, before the onset of flow, is not expected major differences (which was confirmed by the simulations) compared to the cases when $\mu \dot{\gamma} / \tau_o \ll 1$.

The major differences occur after the onset of flow, observed at the velocity evolution curves (Figure 23 and Figure 24), due to the high viscosities involved after the collapse of the gelled microstructure. In this context, inertia plays a much less important role, especially when the inlet pressure is relatively low (Figure 23).

Figure 23 - Time evolution of mean velocity: thixotropy effect
 $P_{inlet} = 2,5 * P_{min}$ and $\mu\dot{\gamma}_1/\tau_o = 1$ [3]

At early times and just after the microstructure collapse, the viscosity of the thixotropic material is lower than the viscosity of the incoming fluid and keeps decreasing until a significant amount of the incoming fluid has entered the tube. At this stage, the flow resistance of the incoming fluid is already important and is becoming progressively larger. Consequently, the velocity reaches a maximum value and then starts decreasing with time (see Figure 24). The structuring level of the thixotropic material starts to increase, causing also a viscosity increase.

In this way, the viscosity of the outgoing fluid tends to approach asymptotically the viscosity of the incoming fluid ($\eta \rightarrow \mu$), as in the case of low inlet pressure, but now from below. Because of this behavior, the velocity evolution curves are no longer monotonic, when the viscosity of the incoming fluid is relatively high.

Figure 24 - Time evolution of mean velocity: thixotropy effect
 $P_{inlet} = 10 * P_{min}$ and $\mu\dot{\gamma}_1/\tau_o = 1$ [3]

3 Detailing of the simulation strategy

3.1. Main assumptions

Due to some features regarding to fluid data obtained and the concept of the experimental apparatus, some assumptions have to be defined in order to allow the appropriate treatment of the comparison between the simulated results and the experimental flowing data.

Regarding to the fluids evaluated, the analysis was structured based on three cases: the first case is the validation of the numerical code implemented on StarWaCS, in its more simplistic simulation, which takes into account the behavior of a non-thixotropic fluid, in this case, the carbopol.

The expectation is that the simulator be capable to represent well the behavior of this fluid, honoring its constitutive equation, giving us the necessary confidence to go further, analyzing also the behavior for more complex fluids, that present thixotropic effects. In this context, these fluids comprise the second and third cases, that consider two fluids with different thixotropic behavior, that are: the laponite with a lower salt concentration (0.0005 mol/l) and the laponite with a higher salt concentration (0.005 mol/l).

The details about these fluids will be presented on the next sections, but some important assumptions related to them were adopted in this work:

- the outgoing fluid (fluid initially inside the pipe, that is displaced) has the same characteristics of the incoming fluid (fluid used to push the previous one). This assumption was considered because the experiments involving shutdown and restart only present this situation.
- for the thixotropic fluids, it is assumed that the steady-state yield stress is equal to zero ($\tau_{y0} = 0$). It means that if the flows stops, it can be easily restarted, if any level of pressure is immediately applied.
- all the samples were pre-sheared and left at rest for twenty minutes before the application of the inlet pressure.
- the values for thixotropic viscosity (laponite cases – this parameter was not measured at the laboratory) were obtained from a comparison between *Houska*

and a *SMT* adjusted model, about the structure parameter evaluation, in steady state conditions, with the inlet pressure increment. In other words, for a specific experiment, in which the *SMT* model was adjusted based on its basic parameters (t_{eq} , η_o and η_∞ fitted to the experimental data), it was assumed that *Houska* model should have the same behavior for the structure parameter variation and the viscosity at steady state conditions, with the inlet pressure increment. This procedure is illustrated in Figure 25.

Figure 25 – Structure parameter (λ) evolution with inlet pressure increment

To calculate the viscosities at steady state conditions, first it was obtained the equation for $\dot{\gamma}$ presented in Eq. (31) below, based on the assumptions that, in Eq. (11), $d\lambda/dt = 0$.

$$\dot{\gamma} = \left(\frac{\left(\frac{a}{\lambda_{eq}} - a \right)}{b} \right)^{\frac{1}{m}} \quad (31)$$

After this, the viscosities were calculated by the *Houska* model equation, presented in Eq. (10). These values are showed in Table 1 below.

Table 1 – Viscosity calculations at steady state conditions

$\tau - \tau_{cl}$ (Pa)	Inlet pressure (PSI)	Δk HOUSKA Evaluation						SMT adjusted	
		λ Houska ($\Delta k = 1.9$ Pa.S)	Houska viscosity calculated	λ Houska ($\Delta k = 8$ Pa.S)	Houska viscosity calculated	λ Houska ($\Delta k = 15$ Pa.s)	Houska viscosity calculated	λ SMT adjusted	SMT viscosity calculated
-	1.4	1.00	INF	1.00	INF	1.00	INF	1	25000.0
0.05	1.5	1.00	INF	1.00	INF	1.00	INF	1	25000.0
0.35	1.6	0.99	732.6	0.997	2709.5	1.00	INF	1	25000.0
0.65	1.7	0.96	294.5	0.99	1360.6	0.998	7805.1	0.97	16069.5
0.95	1.8	0.89	133.0	0.97	593.8	0.990	1988.5	0.94	10329.1
1.25	1.9	0.82	94.1	0.94	357.3	0.98	1224.2	0.91	6639.3
1.65	2.0	0.75	79.1	0.89	231.0	0.96	747.5	0.87	3683.1
1.95	2.1	0.68	64.4	0.82	146.8	0.94	557.3	0.83	2043.1
2.25	2.2	0.62	55.9	0.75	107.9	0.90	353.4	0.80	1313.3
2.55	2.3	0.57	50.6	0.68	84.3	0.86	265.2	0.77	844.1
2.85	2.4	0.54	49.6	0.63	74.1	0.79	174.5	0.74	542.6
3.15	2.5	0.47	40.5	0.57	62.5	0.71	121.3	0.71	348.8
3.45	2.6	0.44	38.9	0.53	57.5	0.66	103.4	0.68	224.2
3.75	2.7	0.42	38.7	0.49	52.6	0.61	89.0	0.66	167.0
4.05	2.8	0.41	40.0	0.46	49.9	0.56	76.9	0.64	124.4
4.35	2.9	0.38	37.5	0.43	47.0	0.52	69.4	0.62	92.6
4.75	3.0	0.35	35.6	0.41	46.9	0.49	66.6	0.59	59.5
5.05	3.1	0.29	28.1	0.36	39.7	0.45	59.5	0.56	38.3
5.35	3.2	0.28	28.2	0.33	36.5	0.41	52.9	0.54	28.5
5.65	3.3	0.27	28.3	0.31	34.9	0.39	51.0	0.53	24.6
5.95	3.4	0.24	25.1	0.29	33.1	0.36	46.8	0.52	21.2
6.25	3.5	-	-	0.27	31.3	0.34	44.7	-	-

Regarding to the performing of the simulations, it was considered that:

- the simulations considered the final time of 500 s. This time was chosen as a maximum value, which comprises the duration period of all the experiments;
- to reproduce the laboratory requirements of the experiments, an inlet pressure is always applied and the simulation is considered representative of the experiment when the same average velocity is achieved at the steady state conditions;
- all the cases considered a fluid completely structured ($\lambda = 1$) at time = 0s of the simulation. The experiments always considered a minimum rest time of the fluid, before the beginning of the restart tests;
- all the experiments analyzed considered the application of inlet pressure reasonably above the minimum pressure to start the flow, i.e., it was not possible to evaluate cases just above the yield stress. The matrix of experiments unfortunately didn't contemplate these situations;
- due to the fact that the restart event was the focus of this work, it was assumed a very low value for the build-up parameter ($a = 0.005$), for both *Houska* and *SMT* models, considering that this value is representative of this phenomenon (at the beginning of the restart will only occur the breakdown of the gel structure);

- the thermal calculations were not taken into account, i.e., the flow for all the cases was considered isothermal, because all the experiments were conducted at a controlled thermal ambient;
- some constitutive parameters of *Houska* model were considered constant during the simulations: b , m and the viscosity parameters (k and Δk). It was due to the fact that the equations which governs the variation of these parameters are function of the temperature. As mentioned at the previous paragraph, the simulations were considered isothermal because the experiments were performed at a constant temperature;
- the discretization of the axial and radial lengths of the pipeline and the definition of the numerical parameters to perform the simulations aimed a good compromise between the quality of the results and the computational time of simulations. The mesh analysis is detailed in the section 3.4.2.

3.2. Description of the experimental apparatus

The experimental apparatus used to perform the experiments is part of the infrastructure installed in the Fluids Mechanics Lab – Laboratory for Complex and *non-Newtonian* Flow, situated at the University of British Columbia. The work involving all the experiments including performance, data monitoring and fluid preparation makes part of the scope of a Ph. D. research under development, conducted at this university by doctoral student Moisés [32], as mentioned before, which kindly provided the experimental data used in this work.

The apparatus is detailed at the Figure 26, being composed by a transparent acrylic pipe (for the experiments used here, $\beta = 90^\circ$), with 3,6 meters long and internal diameter of 19,05 mm. The pipe is placed inside fish tanks (two) filled with water to minimize errors due to light refraction, which were back-lit using Light Emitting Diode (LED) stripes. Two first-surface mirrors were also added to the system, to allow the recording of the top view images.

In order to accurately set up the whole system at a specific angle (in this case, β is equal to 90° , horizontal flow), a digital angle meter was adopted capable of measuring to $0,1^\circ$ accuracy.

Figure 26 - Simplified schematic of the experimental apparatus [32]

An Ultrasound Doppler Velocimetry (UDV) is located outside the pipe, at the end of the first fish tank to allow the easy access (part of the system with bare pipe). At 80 cm from the inlet pipe end was placed one pneumatic gate valve (hand-operated PVC globe valve to mitigate transient effects due to its very short time response). Before this valve was inserted a pressure gage.

Two pressurized tanks of acrylic were built to pump the fluids into the flow loop. This configuration aims to avoid possible disturbances induced by the pump. The flow rate is recorded before the discharge of the fluids to the drain, through a magnetic flow meter.

To complement the experimental data obtained, two high-speed digital cameras were employed to capture the images of the flow inside of each fish tank.

All the mentioned instrumentation allowed the obtaining of three main types of measured data (detailed in the next section), for the scope of this work:

- a) Pressure data – the pressure upstream the gate valve was monitored by a 150 psi pressure gage transducer; its calibration curve was provided by the manufacture.
- b) Velocity data – the UDV equipment allows the quantitative understanding of fluid velocity variations, with a non-intrusive approach and without a requirement of a transparent medium. The model used was DOP2000 (*Signal Processing S.A.*), 8 MHz, 5 mm transducers (TR0805LS), with a duration of 0,5 μ s.

The UDV technique is based on sending the sound pulse and receipt of its echo, allowing the measurement of the flow velocity projection on the ultrasound beam. Through the time elapsed between the pulse and the received echo, the distance of the particles from the transducers is computed. The associated increase/decrease of the Doppler frequency shift gives the value of the velocity at each distance. Reflection effects at the lower wall of the pipe affect the velocity measurement locally; due to this fact it is hard to measure the zero velocity at the lower wall.

The acquisition time of the velocity profiles was not constant for all the experiments. It was considered a lower acquisition for experiments with high

mean velocities. In these cases, the signal noise increased with the reduction of the acquisition time.

c) Flow rate data – a magnetic flow meter was used (Omega, low-flow type), which can be applied to fluids with varying viscosities and densities, whose conductivity is higher than $20 \mu s$.

The flow rate calibration was performed for each fluid and it consists of integrating the output flow rate signal (Volts) over time (s), comparing with the produced volume (m^3).

The mass produced (m) during fluid flow in the loop was measured with Sartorium scale (1 g readability) located after the flowmeter and the density measured with Anton Paar density meter, DMA 15N (resolution of 0,0001 g/cm³). From the total mass and fluid density values was possible to calculate the volume ($V = m/d$). This procedure was performed at different flow rates (and repeated for all the concentrations and types of fluid evaluated) allowing the linear regression of the data, with the obtaining of the linear coefficient and the flow rate error. The conversion from the signal unity (Volts) to flow rate unity (mL/s) is obtained by Eq. (32) presented below:

$$Q = LC * (V - 1) \quad (32)$$

where LC = linear coefficient and V = volts.

An example of the relationship between the concentration and the linear coefficient observed at the experiments is presented in Figure 27. In this case, the curve was obtained for the carbopol, that is the fluid used to validate the model implemented on *StarWaCS* simulator, due to its simpler behavior, which is not thixotropic.

Figure 27 - Relationship between concentration and linear coefficient for carbopol [32]

Three ways to obtain the mean values of flow rate (triple check) at the experiments were: 1) the measurement obtained by the flow meter (which is converted to mL/s using Eq. (32); 2) the use of the density and the total mass produced data obtained in the test; 3) area integration of velocity profile to obtain the mean velocity and, consequently, the flow rate at the steady-state. In this case, it will be an estimated value, because some mass volume will be produced (and measured), after the shutdown (when the flow stops).

More details about the specification of the instrumentation and the experimental apparatus can be provided by Moisés [32].

3.3. Experimental data presentation

It was performed many experiments at the laboratory simulating the displacement of a gelled fluid inside the pipeline by the same fluid, applying an inlet pressure. The main objectives were to observe how long the fluid takes to flow and reach the steady-state condition and the measurement of flow rates and velocity profiles during the restart process.

The fluid used at the experiments was the laponite, due to its thixotropic behavior. Moreover, the carbopol also was considered at the studies, to simulate the non-thixotropic behavior, being used to validate the numerical code for less complex simulations, involving parameters that are easier to obtain at the laboratory.

To obtain fluids with different characteristics regarding to the constitutive parameters (K , n , τ_o , etc.), it was prepared samples with different concentrations of laponite and salt. To perform the simulations presented in this work, it was considered only the experimental data obtained with laponite concentration of 1,5%, because it was the concentration that could make available all the data of interest for this work (flow rates associated with inlet pressures applied on the fluids and the respective velocity profiles).

Regarding to the thixotropic evaluation, two different concentrations of salt were considered for the same laponite concentration (1,5%): 0,0005 mol/l and 0,005 mol/l. The carbopol, due to its non-thixotropic behavior, was used to validate the simulation results, when the thixotropy is not being considered inside the numerical code of the StarWaCS simulator. The following Table 2 summarizes the fluids and their respective characteristics considered on the scope of this work.

Table 2 – Fluids used at the simulations and their respective characteristics (obtained by regression of the experimental data)

Parameters for the evaluated fluids (obtained by regression of the experimental data)										
Types of Fluids	n	K	Δk Houska	τ_{Y1} Houska or τ_{Y0} SMT (Pa)	τ_{Y0} Houska (Pa)	Minimum pressure to start-up (PSI)	η_o (Pa.s)	η_∞ (Pa.s)	Amb. Temp. (°C)	Density (kg/m ³)
Carbopol 0.08%	0.49	1.99	–	4.5	0	1.45	–	–	25	0.9979
Laponite 1.5% (0.0005 mol/L Salt Concentration)	0.76	0.35	0.35	0.2	0	0.06	2,500	~ 0.01	25	1.0060
Laponite 1.5% (0.005 mol/L Salt Concentration)	0.27	1.90	1.90	4.6	0	1.48	25,000	~ 0.01	25	1.0063

At the following section, it will be presented the experimental data obtained from viscosimetry and creep flow tests for each fluid and the details for the regressions done in each case, being the treatment of all these provided raw fluid data [32] part of the scope of this work.

For each fluid, a sequence of experiments was performed increasing the inlet pressure in steps, intending to reach the beginning of the flow (yield stress forecast). This process was continued even for the inlet pressures above the minimum pressure to start the flow, to allow the measurement of the pairs shear stress x shear rate (based on steady-state achievement for each stress), necessary to plot the flow curves.

As mentioned above, the pressures, the velocity profiles and the flowrates were obtained for each experiment, which will be properly presented on the following sections.

3.3.1. Fluids characterization

The experimental data obtained from viscosimetry and Creep Flow Tests, both performed by Moisés [32], was used to perform the fluids characterization in the scope of this work, to obtain the parameters that are necessary as input to the simulator.

Carbopol

As showed in the Table 2, carbopol with 0.08% concentration was used to validate the numerical code of StarWaCS for restart simulations without considering the thixotropic effects (more simplistic case).

Performing the data regression based on the Eq. (9), it was possible to obtain the constitutive equation for this fluid, based on H-B model. The data used to perform this regression was obtained through a viscosimetry test (see Table 3 below) and confirmed by the Creep Flow Tests (Figure 29).

Table 3 – Data obtained from viscosimetry test with carbopol (0,08%)

Index	σ (Pa)	$\dot{\gamma}$ (s ⁻¹)	$\tau - \tau_0$ (Pa)	τ_0 (Pa)	4.5 Pa
				$\ln \dot{\gamma}$	$\ln (\tau - \tau_0)$
1	7.01	1.00	2.01	0,00000	0.69863
2	7.24	1.26	2.24	0.23032	0.80603
3	7.52	1.59	2.52	0.46058	0.92545
4	7.84	2.00	2.84	0.69064	1.04239
5	8.17	2.51	3.17	0.92108	1.15468
6	8.55	3.16	3.55	1.15120	1.26667
7	8.97	3.98	3.97	1.38153	1.37977
8	9.43	5.01	4.43	1.61184	1.48908
9	9.95	6.31	4.95	1.84214	1.59858
10	10.52	7,94	5.52	2.07242	1.70838
11	11.16	10.00	6.16	2.30259	1.81808
12	11.87	12.59	6.87	2.53290	1.92716
13	12.68	15.85	7.68	2.76317	2.03862
14	13.56	19.95	8.56	2.99323	2.14710
15	14.56	25.12	9.56	3.22366	2.25759
16	15.68	31.62	10.68	3.45379	2.36837
17	16.93	39.81	11.93	3.68412	2.47906
18	18.32	50.12	13.32	3.91442	2.58927
19	19.95	63.10	14.95	4.14472	2.70471
20	21.76	79.44	16.76	4.37500	2.81900
21	23.84	100.00	18.84	4.60517	2.93598
22	26.07	125.90	21.07	4.83550	3.04785
23	28.69	158.50	23.69	5.06575	3.16505
24	31.83	199.50	26.83	5.29581	3.28952
25	35.15	251.20	30.15	5.52625	3.40618
26	39.04	316.20	34.04	5.75637	3.52754
27	43.54	398.10	38.54	5.98670	3.65170
28	48.63	501.20	43.63	6.21701	3.77574
29	55.08	631.00	50.08	6.44731	3.91362

It is important to emphasize that, for carbopol, the performing of the viscosimetry test provided the measurement of different points of the flow curve, allowing a very good adjustment of the data through the regression showed in Figure 28. For laponite samples, this test was not performed, due to the long time required to obtain each point of the flow curve, due to the thixotropic effects of these fluids. Therefore, the regression was done with only three points of the flow curve obtained from the Creep Flow Tests data, as detailed in the next item.

Figure 28 – Carbopol 0,08% – Regression based on viscosimetry data

In Figure 29, the evolution curves for strain rate obtained for different inlet pressures are presented. The creep flow test consists on the application of a constant pressure at the inlet tube during a specified period, along which the fluid is observed regarding to its strain behavior (if there is or not a stabilization tendency of it along the time). Observing the curves it is possible to see that they are consistent with the yield stress obtained by the regression based on H-B model.

Figure 29 – Carbopol 0,08% – Curves for different values of shear stress obtained at the Creep Flow Tests [32]

Laponite

For the laponite samples analyzed, unfortunately the viscosimetry test was not performed. So, for these cases, the regression to obtain the constitutive equations for each fluid was done based on three points (for three values of shear stress), where the steady state conditions were reached (or almost reached), in the curves obtained at the Creep Flow Tests.

In the following tables and figures is showed the measured data for both salt concentration of the laponite samples and plotted the respective curves (strain rate x time) observed at the Creep Flow Tests, being also detailed the regression done for each case.

Salt concentration of 0.0005 mol/l

Figure 30 – Creep flow test for the laponite with lower salt concentration (0.0005 mol/l) [32]

Based on the curves showed in Figure 30, it is observed that the strain behavior over the time remains practically constant when is applied a shear stress of 0.5 Pa. The same behavior is observed for the higher shear stresses. It was assumed that these three curves (for 0.5 Pa, 1.2 Pa and 4.0 Pa) reached approximately the steady state condition, being their pairs of strain rate rate versus shear stress considered as different points of the flow curve representative of this fluid.

Such information are summarized in Table 4 below, which were the input to perform the regression, presented in Figure 31.

Table 4 – Points considered to obtain the flow curve for laponite with lower salt concentration (0.0005 mol/l)

Steady-state data from Creep Flow Tests ($\tau_{y1} = 0.2$ Pa)				
$\dot{\gamma}$ (s ⁻¹)	τ (Pa)	$\tau - \tau_0$	$\ln \dot{\gamma}$	$\ln (\tau - \tau_0)$
0.82	0.5	0.3	-0.198	-1.204
4.01	1.2	1.0	1.386	0.000
23.08	4.0	3.8	3.135	1.335

Figure 31 – Laponite 0,0005 mol/l – Regression based on Creep Flow Tests

Salt concentration of 0.005 mol/l

Figure 32 - Creep flow test for the laponite with higher salt concentration (0.005 mol/L) [32]

Based on the curves showed in Figure 32, it is observed that the strain behavior over the time remains practically constant when is applied a shear stress of 8.0 Pa. The same behavior is observed for the higher shear stresses. It was assumed that these three curves (for 8.0 Pa, 15.0 Pa and 18.0 Pa) reached

approximately the steady state condition, being their pairs of strain rate rate versus shear stress considered as different points of the flow curve representative of this fluid.

The Table 5 presents the points considered as input to perform the regression, presented in Figure 33.

Table 5 – Points considered to obtain the flow curve for laponite with lower salt concentration (0.005 mol/l)

Laponite (0.005 mol/l of salt concentration)				
Steady-state data from Creep Flow Tests ($\tau_{y1} = 4.6$ Pa)				
$\dot{\gamma}$ (s ⁻¹)	τ (Pa)	$\tau - \tau_0$	$\ln \dot{\gamma}$	$\ln (\tau - \tau_0)$
8.50	8.0	3.4	2.140	1.224
590.00	15.5	10.9	6.380	2.389
1270.00	17.8	13.2	7.147	2.576

Figure 33 – Laponite 0,005 mol/l – Regression based on Creep Flow Tests

3.3.2.

Fluid flow, inlet pressure and velocity profiles data

As mentioned before (section 3.2), for all the experiments, it was measured the flow rates along time and respective inlet pressures. Besides this, for each experiment the velocity profiles were obtained along the time, for the section in the middle of the way, through which the flow will pass.

For the example in Figure 34, the application of the inlet pressure begins at time $t = 0$ s and it is possible to observed clearly the thixotropy effect, when the flow starts just a few seconds after the application of the inlet pressure.

Figure 34 – Data obtained in an experiment with laponite [32]

In Figure 35, is presented an example for one measured velocity profile for carbopol, showing a good adjustment to the respective simulated data. This case will be one more time presented in the next chapter.

Figure 35 – Example of a measured velocity profile [32], reasonably adjusted to the simulated data

3.4.

The IFP ColdStart model (StarWaCS-1.5D methodology)

The 1.5D model allows a more accurate simulation of this process, while keeping the reasonable computing time of the 1D version. The version of StarWaCS used in this work was implemented with a new Finite Volume scheme in which the velocity is still one dimensional but is allowed to vary in both radial and axial directions. Because of this compromise between the 1D and 2D model, this version was denominated by 1.5D.

3.4.1.

Problem formulation on StarWaCS

For this kind of problem the unknowns are the axial velocity component $\bar{w}$ and the pressure. The assumption for the pressure is its dependency on the axial position z only, being supposed to be constant in a cross section of the pipe, which implies that the mass conservation equation is written with the mentioned axial velocity $\bar{w}$. However, radial effects are taking into account through the axial velocity component since $\bar{w}$ is allowed to depend on both r and z . In Figure 36 is presented an example of the geometry and boundary conditions for the restart problem.

The version used for this work has implemented both models mentioned in the section 2.3 and, as mentioned before, one of the assumptions assumed was that the incoming fluid and outgoing fluid are the same.

Figure 36 – A 2D sketch of the waxy crude oil restart problem: boundary conditions for the velocity-pressure problem [29]

Lubrication model for the velocity-pressure problem

Prior to the Finite Volume integration of governing equations into a discrete system, it is necessary to derive a simplified model that combines the advantages of the fully 1D model and the accuracy of the fully 2D model. To achieve this task, classical scaling arguments was adopted in order to reduce the model into a tractable lubrication-like model.

The constraint 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. This fits very well the lubrication theory.

The simplification to 1.5D situations is presented in the context of the lubrication approach, based on the original governing equations (Eq. (33) and Eq. (34)) of the problem:

$$\rho \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) + \nabla p = \nabla \cdot \tau + \rho g \quad (33)$$

$$\chi_T \left(\frac{\partial p}{\partial t} + u \cdot \nabla p \right) + \nabla \cdot u = 0 \quad (34)$$

Estimating the order of the terms involved in the governing equations, considering the momentum equations written in cylindrical coordinates and performing some algebraic operations, the momentum equations can be written as:

$$0 = - \frac{\partial p}{\partial r} \quad (35)$$

$$\rho \frac{\partial w}{\partial t} = - \frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial r \tau_{rz}}{\partial r} \quad (36)$$

Based on this, the mass conservation reduces to:

$$- \chi_T \left(\frac{\partial p}{\partial t} + w \frac{\partial p}{\partial z} \right) = \frac{1}{r} \frac{\partial ru}{\partial r} + \frac{\partial w}{\partial z} \quad (37)$$

Integrating this equation over the cross section of the pipeline and dividing by the cross-section area πR^2 leads to:

$$- \chi_T \left(\frac{\partial p}{\partial t} + \bar{w} \frac{\partial p}{\partial z} \right) = \frac{\partial \bar{w}}{\partial z} \quad (38)$$

where:

$$\bar{w} = \frac{1}{\pi R^2} \int_0^R w 2\pi r dr \quad (39)$$

Finally, the system of equations to be solved in the lubrication-style simplified model is:

$$-\chi_T \left(\frac{\partial p}{\partial t} + \bar{w} \frac{\partial p}{\partial z} \right) = \frac{\partial \bar{w}}{\partial z} \quad (40)$$

$$\rho \frac{\partial w}{\partial t} = -\frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial r \tau_{rz}}{\partial r} \quad (41)$$

$$\tau_{rz} = \begin{cases} (k + \lambda \Delta k) \frac{\partial w}{\partial r} + \frac{\frac{\partial w}{\partial r}}{\left\| \frac{\partial w}{\partial r} \right\|} (\tau_{y0} + \tau_{y1}) & \text{if } \|\tau_{rz}\| \geq \tau_{y0} + \lambda \tau_{y1} \\ \frac{\partial w}{\partial r} = 0 & \text{if } \|\tau_{rz}\| < \tau_{y0} + \lambda \tau_{y1} \end{cases} \quad (42)$$

The equations above contain only the leading order terms, which means that any implementation of the model should consider, at least, these terms.

Mathematical formulation

Just for the sake of clarity, the different steps of the adopted solution algorithm in StarWaCS are listed now, using the standard calculation for *Houska* model (of course, these steps were adapted to attend *SMT* model assumptions):

- Initialization of $u^0 = u_0$, $p^0 = p_0$, $d^0 = d_0$, $c^0 = c_0$, and $\lambda^0 = \lambda_0$
- Time loop $t^k = t^{k-1} + \Delta t^k$, $k \geq 1$
 - Solve the velocity-pressure problem

- Compute

$$f = \frac{\rho(c^{k-1})}{\Delta t^k} u^{(k-1)} - \rho(c^{k-1}) u^{k-1} \cdot \nabla u^{k-1} + \rho(c^{k-1}) g \quad (43)$$

$$f' = -\frac{\chi_T(c^{k-1}, p^{k-1})}{\Delta t^k} p^{(k-1)} + \chi_T(c^{k-1}, p^{k-1}) u^{k-1} \cdot \nabla p^{k-1} \quad (44)$$

- Initialization of $u^{k,(0)} = u^{k-1}$, $p^{k,(0)} = p^{k-1}$, $d^{k,(0)} = d^{k-1}$ and $\lambda^0 = \lambda_0$
- for $i \geq 0$
 - Solve the compressible Stokes problem

$$\begin{aligned} & \frac{\rho(c^{k-1})}{\Delta t^k} u^{k,(i+1)} - \nabla \cdot [(2\mu(\dot{\gamma}(u^{k-1}), c^{k-1}, \lambda^{k-1} + k) D(u^{k,(i+1)})) \\ & - \frac{2}{3} \mu(\dot{\gamma}(u^{k-1}), c^{k-1}, \lambda^{k-1}) (\nabla \cdot u^{k,(i+1)}) I] + \nabla \cdot p^{k,(i+1)} = \end{aligned} \quad (45)$$

$$= \nabla \cdot (\lambda^{k,(i)} - k d^{k,(i)}) + f - \frac{\chi_T(c^{k-1}, p^{k-1})}{\Delta t^k} p^{k,(i+1)} - \nabla \cdot u^{k,(i+1)} = f,$$

- Evaluate the strain rate tensor $d^{k,(i+1)}$

$$d^{k,(i+1)} = \begin{cases} 0 & \text{if } \|\lambda^{k,(i)} + k D(u^{k,(i+1)})\| < \tau_0(c^{k-1}, \lambda^{k-1}) \\ \frac{1}{k} (1 - \frac{\tau_0(c^{k-1}, \lambda^{k-1})}{\|\lambda^{k,(i)} + k D(u^{k,(i+1)})\|}) (\lambda^{k,(i)} + k D(u^{k,(i+1)})) & \text{if not} \end{cases} \quad (46)$$

- Update the Lagrange multipliers $\lambda^{k,(i+1)}$

$$\lambda^{k,(i+1)} = \lambda^{k,(i)} + k (D(u^{k,(i+1)}) - d^{k,(i+1)}) \quad (47)$$

- Update the density $\rho^{k,(i)}$

$$\rho^{k,(i)} = \rho_0 e^{\chi_T p^{k,(i)}} \quad (48)$$

- Convergence if

$$\max_{\Omega} |u^{k,(i+1)} - u^{k,(i)}| \leq \epsilon_1 \quad (49)$$

$$\max_{\Omega} |D(u^{k,(i+1)}) - d^{k,(i+1)}| \leq \epsilon_2 \quad (50)$$

- Solve the fluid presence problem

$$\frac{c^k - c^{k-1}}{\Delta t^k} + u^k \cdot \nabla c^{k-1} = 0 \quad (51)$$

- Solve the structure parameter problem

$$\frac{\lambda^k - \lambda^{k-1}}{\Delta t^k} + u^k \cdot \nabla \lambda^{k-1} = a(c^{k-1})(1 - \lambda^{k-1}) - b(c^{k-1})\lambda^{k-1} \dot{\gamma}(u^k)^m \quad (52)$$

- Data output at time t^k
- End if

Finite volume formulation

The calculation domain Ω is subdivided in a finite number of control volumes and the variables (w , p , λ and c) are located in the center of the corresponding control volumes. A discretized grid, presented in Figure 37, is adopted to integrate the discretized form of the continuity and momentum equations.

The 1.5D approach consists in discretizing the z momentum equation on the 2D grid and the continuity equation on the first row of the 2D grid.

Figure 37 – Schematic of the grid adopted to integrate the discretized form of the continuity and momentum equations. [29]

The axial velocity component w is located at the cell faces of the 2D grid whereas the concentration (c) and structure parameter (λ) are cell centered. The pressure is located at the cell center of the 1st row of the 2D grid. The components (d_{zz} , λ_{zz}) of strain rate and Lagrange multipliers tensors are located at the cell

center whereas the non-diagonal components (d_{rz} , λ_{rz}) are located at the grid nodes. This grid, called Marker And Cell (MAC), allows to write first derivatives with a second order centered scheme.

Discretized continuity equation

The continuity equation is discretized on a 1D grid, as showed in Figure 38, since pressure only depends on axial position. In other words, the 1D grid comprises one single cell in the radial direction that spans the pipe radius R .

Figure 38 – Control volume Ω_p for the continuity equation [29]

More detailed information about how the discretized continuity equation and z-momentum equation are implemented in the numerical code of StarWaCs can be found in the reports elaborated by IFP [29][30], which are one of the products of JIP mentioned before.

Operational characteristics of StarWaCs

The program has four different types of simulation, that are:

NORMAL – restart of a waxy crude oil (outgoing fluid) by a *viscoplastic* fluid (incoming fluid) where all the physical fields (velocity, pressure, temperature, structure parameter) are initialized.

This type was the suitable one to apply the simulations that are scope of this work. In this case, the incoming fluid and the outgoing fluid are the same due to the experiments characteristics.

RELOAD – reload any type of simulation, i. e. pursue a simulation by initializing the physical fields with the data of a previous simulation; these data have to be put in *ReloadSavings* directory prior to run the *RELOAD* simulation.

SHUTDOWN – run the flow shutdown of a single non-isothermal *viscoplastic* fluid (outgoing fluid). The shutdown time is given by the *ShutdownTime* parameter. Only a flow rate can be imposed at the pipe inlet for a *SHUTDOWN* simulation. The temperature field at shutdown time is automatically saved in a file named *shutdownTemperature.dat*.

RESTART – restart of a waxy crude oil (outgoing fluid) by a *viscoplastic* fluid (incoming fluid) after a *SHUTDOWN* simulation. The temperature field is not initialized but reloaded from the final time of the *SHUTDOWN* simulation. This data must be put in the *ReloadSavings* directory prior to run the *RESTART* simulation.

In case of *RELOAD* or *RESTART* simulation, the pipeline setup can't be modified, i.e. the parameters of <Pipeline> keyword are automatically reloaded from the *ReloadSavings* directory.

All the input data is filled in a XML format file. XML is designed to transport and store data with simplicity, being a set of rules for encoding documents in machine-readable format.

Regarding to the parameters of the constitutive equation for λ and the boundary conditions for the simulations, some characteristics are presented below:

- the structure parameter can be initialized using either a simple correlation (StandardCorrelation) or a correlation based on the ColdStart methodology (ColdStartCorrelation). The second one allows to compute the structure parameter depending on the thermal and mechanical history. For the scope of this work, the first one was chosen due to the equal treatment given to all the samples before the experiment (pre-shearing and resting) and the isothermal ambient;
- the viscosity (steady-state and thixotropic) and shear thinning coefficients (n) can be set through a constant term or a linear/exponential dependence with the

temperature. In this case, they were set as constants, due to the isothermal ambient considered to perform the experiments;

- the parameters a , b , m and t_{eq} follow the same possibilities described for the viscosities. For the same reasons, they were considered as constants in the simulations;
- The inlet and the outlet pressures can be set through four different types: CONSTANT, DATA_FILE (in which is defined the time variation for the pressure values), RAMP (imposed by filling the parameter ‘InletPressureRampPeriod’ that will govern the ramp equation) and PULSATION (when two parameters are defined: ‘AmplitudeInletPressure’ and ‘PulsationInletPressure’, which govern a sinusoidal behavior for the pressure values). The last two types are also available for the outlet pressure input.

3.4.2. Sensitivity analysis for the mesh

The purpose of this analysis is define the discretizations in time and space of the simulation input, in order to optimize the compromise between simulation results precision and time of computational calculation.

This analysis must provide a solution that leads to simulation results that are mesh independent.

In order to start this evaluation, it were defined the following values to evaluate the convergence criterion: 10^{-5} , 10^{-4} , 10^{-3} , 10^{-2} and 10^{-1} . This parameter is obtained in terms of deviation tolerated for the property values of interest, being defined as:

$$\left| \frac{\delta_t - \delta_{t-1}}{\delta_{t-1}} \right| \quad (53)$$

where δ_t is the value obtained for the parameter at the current timestep and δ_{t-1} is the value obtained at the previous timestep.

The analysis was performed considering the fluid properties for Laponite with 0.005% of salt concentration, detailed in Table 2, which were obtained experimentally. Some initial simulations were performed for this fluid considering conditions more discretized (than these showed in this section) for the apparatus

dimensions and time parameters, in order to define the thixotropy parameters that would be used in this mesh analysis.

Besides this, to perform this evaluation, it was elected the experiment of lower flow rate (and the associated pressure differential and shear rate), that is sufficiently small to promote the flowing at low velocities. This level of shear rate allows the observation of numerical oscillations of low amplitude dependent of the adopted convergence criterion, which probably would not be observed at conditions of higher velocities.

Some simulations assumptions were considered:

- each simulation ends at the final time of 200 s. This value comprises the duration time to reach the steady state condition for the evaluated experiment;
- to reproduce the laboratory requirement of the experiment, an inlet pressure is applied and the simulation is considered representative of the experiment when the same average velocity is achieved at the steady state conditions;
- simulation considered a fluid completely structured ($\lambda = 1$) at time = 0 s.
- it was assumed a very low value for the build-up parameter ($a = 0.005$), for both *Houska* and *SMT* models, considering that this value is representative of the restart phenomenon (at the beginning of the restart will only occur the breakdown of the gel structure).
- the thermal calculations were not taken into account, i.e., the flow was considered isothermal, because the experiment was conducted at a controlled thermal ambient;
- some constitutive parameters of *Houska* model were considered constant during the simulations: b , m and the viscosity parameters (k and Δk). It was due to the fact that the equations which governs the variation of these parameters are function of the temperature. As mentioned at the previous paragraph, the simulations were considered isothermal because the experiments were performed at a constant temperature.

A mesh with 12 points in radial direction was used to test the influence of convergence criterion, with a time increment of 10^{-2} seconds. The shear rate at the pipe wall is a parameter that is only dependent of the structure parameter λ and the elastic strain, at the same position in a current instant of time and in its

respective previous and future times. A good way to observe the influence of convergence criterion along all the cross section of the pipe is through the mean velocity evolution with time.

In Figure 39, is presented the temporal evolution of mean velocity for different values of convergence criterion. It is possible to observe that the curves are very similar, not existing apparent difference between them, being de percentual difference of a maximum of 0.08% between the curves relating to extreme values of the analyzed convergence criteria (10^{-5} and 10^{-1}). The value for convergence criterion assumed to be used for simulations was 10^{-2} .

Figure 39 – Temporal evolution of mean velocity according to sensitivity for convergence criterion

The absence of interference between the different values of convergence criterion is also observed at velocity profiles, as showed in Figure 40.

Figure 40 – Velocity profiles at steady-state condition according to sensitivity for convergence criterion

A second evaluation was performed for temporal mesh, considering the following values for initial timestep value: 10^{-6} , 10^{-5} , 10^{-4} and 10^{-3} . In Figure 41 is presented the temporal evolution for mean velocity, for each timestep analyzed. The maximum difference in mean velocity between the extreme values for initial timestep is about 1.7%. Considering the initial timestep in 10^{-4} , the higher difference for mean velocity, comparing to timestep equal to 10^{-6} , is about 0.09%.

Figure 41 – Mean velocity evolution according to sensitivity for initial timestep value

Another important evaluation is the discretization for radial distance of pipeline. For this analysis, it was considered as initial timestep a value of 10^{-4} and a convergence criterion of 10^{-2} . In Figure 42 is presented the temporal evolution for mean velocity, considering four different values for radial discretization.

Figure 42 – Mean velocity evolution according to sensitivity for radial discretization of pipeline

The maximum difference for mean velocity values considering $dR = 5$ and $dR = 50$ was 2.9%. When the results for $dR = 10$ is compared with that for $dR = 50$, this difference drops to around 0.6%.

Considering that the effect of radial mesh in the variables of restart problem is being evaluated, the velocity profiles are presented in Figure 43. It is possible to see that, with $dR = 10$, the obtained velocity profile matches with those considering higher discretizations, with a maximum difference in values around 0.4%. It is notorious the difference for $dR = 5$, when the velocity profile presents a higher deviation, with a maximum difference of 8% from the curve with $dR = 50$.

Figure 43 – Velocity profiles at steady-state condition according to sensitivity for radial discretization of pipeline

In Table 6 is presented the impact on computational time when the radial discretization is increased. Considering the quantity of simulations to be performed (sensitivity analysis) for each evaluated experiment (different flow rates and fluids characteristics), the discretization for dR between 10 and 20 is clearly more appropriate to maintain a good compromise between quality of simulation results and time to run the simulations.

Table 6 – Computacional times for different radial discretizations (dR)

dR	Computacional time (minutes)
5	3
10	3
20	8
50	30

Based on the results described in this section, the following values for parameters were adopted to run all the simulations, whose results are presented in the next sections:

- Convergence criterion: $\delta = 10^{-2}$;
- Initial timestep: 10^{-4} s;
- Radial discretization: $dR = 12$ (a small refinement that does not impact the computational time when compared to that for $dR = 10$).

4 Analysis of results

This chapter presents the results of the simulations performed, based on the fluids characterization done and the comparison with the experimental data obtained at the laboratory. The main concerns about the comparison between the simulations results and the measured data were:

- 1) the delay observed in some cases to start the flow (delay time) and the elapsed time to achieve the steady state conditions (stabilization time). Both data are important to match with simulation data in order to estimate the parameters of constitutive equations for structure parameter evolution ($d\lambda/dt$). These comparison criteria are detailed below for practical reasons:

Delay time (T_d) $\rightarrow$ elapsed time from the beginning of pressure application until the beginning of motion (when is observed the increase of mean velocity derivative). This moment is identified when the mean velocity starts to increase. This parameter was not considered as a reference in *Houska* evaluation because, for all the situations analyzed, the simulations show an instantaneous increase of the mean velocity (even being very low) at the first seconds of simulation. It can be explained by the way as the constitutive equation for Houska (Eq. (10) is described, meaning that, for a shear stress higher than the yield stress, an immediate shear rate is calculated.

Stabilization time (T_s) $\rightarrow$ elapsed time from the beginning of pressure application until the identification of steady-state condition. The criteria assumed to consider the steady state achievement was the mean velocity variation up to 0.1%.

- 2) velocity profiles and their consistency with the flow rates increment and the nature of the fluids (*shear-thinning* and *thixotropic* effects).

The intermediate times (transient regime) evaluated were defined as a function of the stabilization time (T_s); in this work, due to the immediate or fast

beginning of flow observed in the experiments, it was considered just two (for $T_s \leq 10s$) and three intermediate times to be evaluated (for $T_s > 10 s$):

- for $T_s \leq 10s$ (fluid with lower yield stress - Laponite 0.0005%) $\rightarrow$ the intermediate times are equal to one quarter of stabilization time ($T_s/4$) and the half of stabilization time ($T_s/2$);
- for $T_s > 10 s$ (fluid with higher yield stress - Laponite 0.005%) $\rightarrow$ the intermediate times are equal to one quarter of stabilization time ($T_s/4$), the half of stabilization time ($T_s/2$) and 3 quarters of the stabilization time ($3T_s/4$).

4.1.

Validation of implemented constitutive model in the StarWaCS

In order to validate the numerical code of StarWaCS software, considering the aspects of a more simplistic fluid, the carbopol fluid was chosen, due to its characteristics of shear-thinning and non-thixotropy, which were detailed previously in Table 2.

Furthermore, a large quantity of data was available for this fluid, allowing the execution of the data regression based on data obtained at the viscosimetry tests, to adjust the fluid parameters (k , n , τ_o , etc.), required as input to perform the simulations. These important data were presented previously in Table 3.

The results obtained by the simulations are presented in the following sections.

4.1.1.

Restart behavior for case 1 (Carbopol at 0.08%)

To evaluate the behavior for carbopol, two different ranges for flow rate were chosen, which are presented in Table 7.

Table 7 – Flowrates and respective inlet pressures analyzed for carbopol

Carbopol at 0.08%		
Inlet pressure	Flow rate	Mean velocity
(PSI)	(mL/s)	(m/s)
1.5	1.52	0.005
4.7	9.10	0.031

The results for simulations performed in both situations are presented in Figure 44 and Figure 45.

Figure 44 – Comparison between simulated and measured flow rate [32] and pressure during restart. Lower flow rate case

Figure 45 – Comparison between simulated and measured flow rate [32] and pressure during restart. Higher flow rate case

Due to its non-thixotropic behavior, it was expected no delay time after the application of the inlet pressure. This aspect can be clearly observed in the previous figures. The flow rate behavior follows almost the same pressure signature.

4.1.2. Velocity profiles

One of the outputs obtained by simulation is the velocity profile along the time. The next figures show the good concordance between the simulated and the

measured velocity profiles at the steady state conditions. The profiles were plotted in a normalized form to facilitate the visualization.

On the left side of the profiles is observed some variation between the measured and simulated values. It can be explained by the occurrence of some reflection effects at the lower wall of the pipe, disturbing the interpretation of the measured values locally at this side of the pipe.

Figure 46 – Comparison between simulated and measured [32] velocity profiles at the steady state conditions. Lower flow rate case

Figure 47 – Comparison between simulated and measured [32] velocity profiles at the steady state conditions. Higher flow rate case

4.2.

Houska model evaluation

The experimental data used to compare with simulation results comprises four different experiments (varying the inlet pressure applied) for each fluid (Iaponite with 0.0005% and with 0.005% of salt concentration).

The analysis was divided in two moments:

- 1) Use of data for two experiments comprising the lower and the higher flow rates. These cases were considered in an attempt of adjust the parameters of the constitutive equation for λ evolution ($d\lambda/dt$);

For this, it was performed a sensitivity analysis for parameters m and b of *Houska* model (see Table 8), considering a minimum value (very small) for parameter a (build-up parameter = 0.005); this assumption is explained by the fact that the experiments and simulations always considered the fluid initially at rest. To allow the internal calculations of the numerical code, it is not possible to set this value equal to zero.

The range of values considered to perform the sensitivity analysis, as showed in Table 8, was defined based on order of magnitude of known values for these parameters, measured in laboratory, for some oil samples in which are observed thixotropy effects.

In the next sections are presented all the curves for restart considering each combination of the parameters b and m , plotted together with experimental data, for each fluid and experiment evaluated (see Table 9 and Table 11).

Table 8 – Sensitivity matrix for parameters of λ evolution (*Houska* model)

Sensitivity Analysis - Parameters of constitutive equation for $d\lambda/dt$ - <i>HOUSKA</i> model							
b	m	b	m	b	m	b	m
0.01	0.05	0.03	0.05	0.06	0.05	0.10	0.05
	0.10		0.10		0.10		0.10
	0.25		0.25		0.25		0.25
	0.50		0.50		0.50		0.50

- 2) For the adjusted parameters b and m , the other two intermediate flow rates were considered to confirm the restart times, comparing the delay time and the

stabilization time with the experimental data obtained for these experiments. Besides this, the simulated velocity profiles for each experiment (flow rate) evaluated are presented, comparing with the measured velocity profiles.

4.2.1.

Simulations for case 2 (Laponite 0.0005% of salt concentration)

In Table 9 is showed the experiments analyzed, for the fluid with the lower yield stress value (0.2 Pa) and respective minimum pressure to restart (0.06 PSI), according to Eq. (1), when the compressibility effect is not being taken into account.

It is important to emphasize that the yield stress for laponite increases with the increment of salt concentration.

Table 9 – Flowrates and respective inlet pressures analyzed for laponite (0.0005% of salt concentration)

Laponite (0.0005% of salt concentration) - Measured data			
Inlet pressure (PSI)	Flow rate (mL/s)	Mean velocity (m/s)	Stabilization time (Ts) (s)
1.1	8.70	0.030	6.4
1.8	14.00	0.048	4.5
2.2	16.10	0.056	2.6
2.4	18.30	0.063	1.8

It is possible to observe that the lower inlet pressure presented in Table 9 is much higher than the minimum pressure to restart. It was observed for most of the experiments performed with this fluid (0.0005% of salt concentration). Due to the very small yield stress value and the time scale of the experiments, it is a hard compromise to easily identify the exact moment (i.e. the exact value) for its occurrence.

On the other hand, this aspect confirmed the absence of the delay time after the application of the inlet pressure above the minimum pressure, both for the results of the simulations and the experimental data. These results are presented in the following sections.

4.2.1.1.

Parameters influence during the restart

It was performed a sensitivity analysis for the parameters m and b , as mentioned before (see Table 8), keeping constant the build-up parameter a , in order to evaluate in which conditions these parameters fit to the experimental data. The next items present the simulation results considering each of these combinations between both parameters (b and m) in the λ evolution equation, comparing with the experimental data measured at the laboratory.

Sensitivity to parameters b and m

The next figures present the comparison between the experimental data and the results obtained by simulation regarding to the main restart characteristics (delay time – time that the fluid is at rest - and stabilization time - time to reach the steady state conditions). The flow rate evolution with time is represented by normalized mean velocity (current velocity divided by steady-state velocity).

Results for the lower flow rate

Figure 48 – Sensitivity analysis for parameter b ($m = 0.05$) – Lower flow rate
Experimental data [32] x Simulated data (Houska model)

Figure 49 – Sensitivity analysis for parameter b ($m = 0.10$) – Lower flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 50 – Sensitivity analysis for parameter b ($m = 0.25$) – Lower flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 51 – Sensitivity analysis for parameter b ($m = 0.50$) – Lower flow rate
Experimental data [32] x Simulated data (*Houska* model)

Results for the higher flow rate

Figure 52 – Sensitivity analysis for parameter b ($m = 0.05$) – Higher flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 53 – Sensitivity analysis for parameter b ($m = 0.10$) – Higher flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 54 – Sensitivity analysis for parameter b ($m = 0.25$) – Higher flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 55 – Sensitivity analysis for parameter b ($m = 0.25$) – Higher flow rate
Experimental data [32] x Simulated data (*Houska* model)

Evaluation of the sensitivity analysis

The figures above show that the variation for parameter b is much more sensitive than the variation for parameter m . This is explained by the fact that, in constitutive equation for *Houska* (Eq. (11)), the first parameter multiplies directly the breakdown term, whereas parameter m is as an exponential in the same term. Thereafter, we can say that the delay time (T_d) is more sensitive to parameter b .

For both lower and higher flow rates, it was not possible to find a unique combination for parameters b and m that could fit the experimental data with the simulated data. Based on the previous figures showed, it could only be identified a tendency between these parameters, for both experiments, which is presented in Figure 56. Both curves follow the same behavior, being parallel each other.

This tendency is quite intuitive, considering that the increase of breakdown term b leads to the decrease of parameter m , which is the positive exponent of the breakdown term.

Figure 56 – Behavior curves for b and m combinations that fit the experimental data (for higher and lower flow rate cases) – *Houska* model

Results for the intermediate flow rates

Considering the fact that it was not found a unique combination for parameters b and m that could fit the simulated restart data with the experimental data, just to check if the points plotted in Figure 56 are in a realistic order of magnitude, it was considered an average curve between these two curves and used the extreme values for combinations of b and m to perform the simulation for the intermediate flow rates (Figure 57 and Figure 58). These combinations are presented in bold in Table 10.

Table 10 – Mean parameters b and m to be verified for intermediate flow rates

b	m
0.01	2.5
0.03	1.9
0.06	1.6
0.10	1.4

Figure 57 – Verification of adjusted parameters b and m for the intermediate flow rate (14.0 mL/s) – Houska model

Figure 58 – Verification of adjusted parameters b and m for the intermediate flow rate (16.1 mL/s) – Houska model

As said before, due to the difference between the minimum pressure to start the flow and the applied inlet pressures at the experiments, no delay is observed at the restart, for this fluid.

Although the simulations present a restart that is agreeing with the experimental data in order of magnitude, it is possible to see that the simulated curves show an immediate increase of the mean velocity, just after the time = 0s (see Figure 48 to Figure 55). It is not physically correct, regardless of being explained by the Eq. (10) which shows that, for a shear stress above the yield stress, an immediate shear rate is calculated. This is even more evident when this

behavior is compared with the experimental data showed in Figure 57 and Figure 58, where the first seconds are in zoom to emphasize this issue.

4.2.1.2. Velocity profiles evaluation

The velocity profiles measured for each experiment listed in Table 9 are presented now, comparing with respective velocity profiles obtained by simulation (for combinations of parameters b and m that fit the experimental data). The velocity profiles are presented in a normalized form to facilitate the visualization.

Considering a short time to restart the flow for these experiments, three moments were considered to compare simulated data with experimental data, referred to stabilization time (T_s): $T_s/4$, $T_s/2$ and T_s .

It is possible to observe a very good concordance between the measured and the simulated data, for all the flow rates evaluated. The velocity profiles were checked with terms of mean velocity, considering the calculation of the integral for experimental data, for comparison with the mean velocity obtained by the measured data (measured flow divided by the pipeline area). For this case, the maximum difference obtained was about 3%.

The shape of velocity profiles is according to the expectation, considering that, for this fluid, the evaluated experiments considered inlet pressures relatively far away from the minimum pressure (associated to the yield stress) to start the fluid displacement; because of this, the plug region of the profile is practically not observed (very small region), being as observed for laminar flows.

Lower flow rate (8.7 mL/s)

Figure 59 – Measured data [32] x simulated data*
 (*Houska model for b and m combinations presented in Table 10)

Intermediate flow rate (14.0 mL/s)

Figure 60 – Measured data [32] x simulated data*
 (*Houska model for b and m combinations presented in Table 10)

Intermediate flow rate (16.1 mL/s)

Figure 61 – Measured data [32] x simulated data*
 (*Houska model for b and m combinations presented in Table 10)

Higher flow rate (18.3 mL/s)

Figure 62 – Measured data [32] x simulated data*
 (*Houska model for b and m combinations presented in Table 10)

4.2.2.

Simulations for case 3 (Laponite 0.005% of salt concentration)

In Table 11 is showed the experiments analyzed, for the fluid with the higher yield stress value (4.6 Pa) and respective minimum pressure to restart (1.45 PSI), according to Eq. (1), when the compressibility effect is not being taken into account.

Table 11 – Flowrates and respective inlet pressures analyzed for laponite (0.005% of salt concentration)

Laponite (0.005% of salt concentration) - Measured data			
Inlet pressure (PSI)	Flow rate (mL/s)	Mean velocity (m/s)	Stabilization time (Ts) (s)
1.8	13.20	0.046	110.0
2.2	22.50	0.078	97.7
2.9	32.40	0.112	76.2
3.5	35.60	0.123	50.2

For this fluid, the lower inlet pressure applied (1.8 PSI) is very close to the minimum pressure to restart. Regarding to the experiments performed with this fluid, this aspect was important to observe the thixotropic effects, that are less perceived when this difference get even higher.

4.2.2.1.

Parameters influence during the restart

It was performed a sensitivity analysis for the parameters m and b , as mentioned before (see Table 8), keeping constant the build-up parameter a , in order to evaluate in which conditions these parameters fit to the experimental data.

The next items present the simulation results considering each of these combinations between both parameters (b and m) in the λ evolution equation ($d\lambda/dt$), comparing with the experimental data measured at the laboratory.

Sensitivity to parameters b and m

The next figures present the comparison between the experimental data and the results obtained by simulation regarding to the main restart characteristics (delay time and time to reach the steady state conditions), considering the experiments with the lower and the higher flow rates.

Results for the lower flow rate

Figure 63 – Sensitivity analysis for parameter b ($m = 0.05$) – Lower flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 64 – Sensitivity analysis for parameter b ($m = 0.10$) – Lower flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 65 – Sensitivity analysis for parameter b ($m = 0.25$) – Lower flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 66 – Sensitivity analysis for parameter b ($m = 0.50$) – Lower flow rate
Experimental data [32] x Simulated data (*Houska* model)

Results for the higher flow rate

Figure 67 – Sensitivity analysis for parameter b ($m = 0.05$) – Higher flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 68 – Sensitivity analysis for parameter b ($m = 0.10$) – Higher flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 69 – Sensitivity analysis for parameter b ($m = 0.25$) – Higher flow rate
Experimental data [32] x Simulated data (*Houska* model)

Figure 70 – Sensitivity analysis for parameter b ($m = 0.50$) – Higher flow rate
Experimental data [32] x Simulated data (*Houska* model)

Evaluation of the sensitivity analysis

As observed for case 2 (laponite with 0.0005% of salt concentration), the figures above show that the variation for parameter b is much more sensitive than the variation for parameter m . This is explained by the fact that, in constitutive equation for *Houska* (Eq. (11)), the first parameter multiplies directly the breakdown term, whereas parameter m is as an exponential in the same term. Thereafter, we can say that the delay time (T_d) is more sensitive to parameter b .

For this fluid, the *Houska* model showed (as observed with the laponite less concentrated) that is not possible to have a minimum predictability for the parameters b and m , when compared the simulated date with the experimental

data, for both flow rates analyzed. In this case is even worst, because it was not observed any tendency between these parameters, even the intuitive thought that they supposed to be inversely proportional each other, as presented in Figure 56.

Trying to understand this fact, the equation of structure evolution ($d\lambda/dt$) for *Houska* model was evaluated, regarding to the shear stress behavior. It is observed that for shear stress values less than 1, the increment of parameter m leads to the decrease of the breakdown term. The relationship of direct proportionality only occurs for values of shear rate above 1. For the experiments evaluated to this fluid, in which a relative delay time is observed, this effect can be contributing to the no predictability of the parameters b and m .

It is expected the increase of the unstructuring rate with the increase of shear rate, but not the inversion of this behavior (decrease of the unstructuring rate with increase of the shear rate), even for low shear rates ($\dot{\gamma} < 1$).

Performing the method of “trial and error”, two combinations of parameters b and m inside the investigated range (see Table 12) promote a reasonable concordance between the simulated and the experimental data, simultaneously for the lower and the higher flow rate cases, which are presented in Figure 71 and Figure 72, respectively.

Table 12 – Combinations of parameters b and m that allowed the fit of the simulated results to the experimental data

Lower and higher flow rates	
b	m
0.06	0.25
0.10	0.55

Figure 71 – Restart for both combinations of parameters b and m
Experimental data [32] x Simulated data (*Houska* model) - Lower flow rate

Figure 72 – Restart for both combinations of parameters b and m
Experimental data [32] x Simulated data (*Houska* model) - Higher flow rate

Results for the intermediate flow rates

Considering the combinations for b and m showed in Table 12, the simulated data was also compared with the experimental data for intermediate flow rates (Figure 73 and Figure 74), in order to verify the consistence with the previous simulation results.

Figure 73 – Verification of adjusted parameters b and m for the intermediate flow rate (22.5 mL/s) – *Houska* model

Figure 74 – Verification of adjusted parameters b and m for the intermediate flow rate (32.4 mL/s) – *Houska* model

The effect observed for the other fluid at the beginning of the simulation (first seconds) is applicable for this one, but in a much smaller scale. Although the simulations present a restart that is agreeing with the experimental data in order of magnitude, the simulated curves show small values for the mean velocity at beginning of the simulation, even considering the fluid totally structured.

4.2.2.2. Velocity profiles evaluation

The velocity profiles simulated considering *Houska* model (for combinations of parameters b and m that fit the experimental data) are now

presented for all the experiments evaluated for laponite with 0.005% of salt concentration, comparing with the measured velocity profiles. The velocity profiles are presented in a normalized form to facilitate the visualization.

Considering a time a little bit longer to restart the flow for these experiments, four moments were considered to compare simulated data with experimental data, referred to stabilization time (T_s): $T_s/4$, $T_s/2$, $3T_s/4$ and T_s .

It is possible to observe a very good concordance between the measured and the simulated data, for all the flow rates evaluated. The velocity profiles were checked with terms of mean velocity, considering the calculation of the integral for experimental data, for comparison with the mean velocity obtained by the measured data (measured flow divided by the pipeline area). For this case, the maximum difference obtained was about 5%.

The shape of velocity profiles is according to the expectation, considering that, for this fluid, the evaluated experiments considered inlet pressures relatively near the minimum pressure (associated to the yield stress) to start the fluid displacement; because of this, the plug region of the profile is significant (fluid with higher yield stress, although considered higher flow rates).

Lower flow rate (13.2 mL/s)

Figure 75 – Measured data [32] x simulated data*
 (*Houska model for b and m combinations presented in Table 12)

Intermediate flow rate (22.5 mL/s)

Figure 76 – Measured data [32] x simulated data*
 (*Houska model for b and m combinations presented in Table 12)

Intermediate flow rate (32.4 mL/s)

Figure 77 – Measured data [32] x simulated data*
 (*Houska model for b and m combinations presented in Table 12)

Higher flow rate (35.6 mL/s)

Figure 78 – Measured data [32] x simulated data*
 (*Houska model for b and m combinations presented in Table 12)

In general, a good concordance is observed between the measured and simulated velocity profiles.

When the flow rate is increased, some difference is observed at the edges of the velocity profiles, which can be explained by the treatment of the experimental data. In these cases, it was observed some inefficiency in the velocities measurement, due to reflection effects observed locally at the experimental apparatus.

4.3. SMT model evaluation

Similarly to what was performed for *Houska* model, the experimental data used to compare with simulation results considering the *SMT* model comprises four different experiments (varying the inlet pressure applied) for each fluid.

The analysis was also divided in two moments:

- 1) Use of data for two experiments comprising the lower and the higher flow rates. These cases were considered in an attempt of adjust the parameters of the constitutive equation for λ evolution ($d\lambda/dt$);

For this, it was performed a sensitivity analysis for parameters t_{eq} and b of *SMT* model (see Table 13), considering a minimum value for parameter a (build-up parameter = 0.005); this assumption is explained by the fact that the experiments and simulations always considered the fluid initially at rest. To allow the internal calculations of the numerical code, it is not possible to set this value equal to zero.

The range of values considered to perform the sensitivity analysis, as showed in Table 13, was defined based on order of magnitude of known values for these parameters, measured in laboratory, for some oil samples in which are observed thixotropy effects.

In the next sections are presented all the curves for restart considering each combination of the parameters b and m , plotted together with experimental data.

Table 13 – Sensitivity matrix for parameters of λ evolution (*SMT* model)

Sensitivity Analysis - Parameters of constitutive equation for $d\lambda/dt$ - <i>SMT</i> model							
b	t_{eq}	b	t_{eq}	b	t_{eq}	b	t_{eq}
0.007	0.10	0.009	0.10	0.01	0.10	0.03	0.10
	0.50		0.50		0.50		0.50
	1.00		1.00		1.00		1.00
	1.50		1.50		1.50		1.50

- 2) For the adjusted parameters b and t_{eq} , the other two intermediate flow rates were considered to confirm the restart times, comparing the delay time and the stabilization time with the experimental data obtained for these experiments. Besides this, the simulated velocity profiles for each experiment (flow rate) evaluated are presented, comparing with the measured velocity profiles.

The next items will presented the results for simulations considering the both fluids evaluation, according to the operational conditions listed in Table 9 and Table 11.

4.3.1.

Simulations for case 2 (Laponite 0.0005% of salt concentration)

The comparison between simulated and measured data are now presented for the fluid with lower value of yield stress. In this case, no delay time is observed, due to the significant difference between the minimum required pressure to start-up the flow and the minimum inlet pressure applied.

In the next items, these comparisons are separated by the restart parameters (delay time and stabilization time) and the velocity profiles.

4.3.1.1.

Parameters influence during the restart

It was performed a sensitivity analysis for the parameters t_{eq} and b , as presented before (see Table 13), in order to evaluate in which conditions these parameters fit to the experimental data. The next items present the simulation results considering each of these combinations between both parameters in the λ evolution equation, comparing with the experimental data measured at the laboratory.

Sensitivity to parameters b and t_{eq}

The next figures present the comparison between the experimental data and the results obtained by simulation regarding to the main restart characteristics (delay time and time to reach the steady state conditions), for each combination of b and t_{eq} and each flow rate evaluated (lower and higher values).

Results for the lower flow rate

Figure 79 – Sensitivity analysis for parameter b ($t_{eq} = 0.1$) – Lower flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 80 – Sensitivity analysis for parameter b ($t_{eq} = 0.5$) – Lower flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 81 – Sensitivity analysis for parameter b ($t_{eq} = 1.0$) – Lower flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 82 – Sensitivity analysis for parameter b ($t_{eq} = 1.5$) – Lower flow rate
Experimental data [32] x Simulated data (*SMT* model)

Results for the higher flow rate

Figure 83 – Sensitivity analysis for parameter b ($t_{eq} = 0.1$) – Higher flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 84 – Sensitivity analysis for parameter b ($t_{eq} = 0.5$) – Higher flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 85 – Sensitivity analysis for parameter b ($t_{eq} = 1.0$) – Higher flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 86 – Sensitivity analysis for parameter b ($t_{eq} = 1.5$) – Higher flow rate
Experimental data [32] x Simulated data (*SMT* model)

Evaluation of the sensitivity analysis

For *SMT* model, the figures above show that the delay time is more sensitive to variation for parameter t_{eq} than the variation for parameter b . On the other hand, the steps considered for its values in the evaluated matrix (Table 13) is much higher (0.5) than that considered for parameter b (0.02).

Thereafter, we believe that both parameter b and t_{eq} have some importance in *SMT* model in terms of impact on delay time (T_d), when a sensitivity analysis is considered.

It was observed, in the evaluation for both lower and higher flow rates cases, a linear tendency considering the combinations for parameters b and t_{eq} that

promote the matching of simulated data with measured data, which is represented in Figure 87. These parameters have influence on the constitutive equation for $d\lambda/dt$, being input parameters at StarWaCS. The curves for lower and higher flow rates are superimposed in the graph below.

Figure 87 – Behavior curves for b and t_{eq} combinations that fit the experimental data (for higher and lower flow rate cases) – *SMT* model

The relationship between parameters b and t_{eq} behaviors presented above is intuitive for this model, since that if the breakdown term b is being increased, the parameter t_{eq} must increase to match the same experimental data (same time to stabilization for each specific flow rate case), because higher is t_{eq} , longer is the time to restart and stabilize the flow.

On the other way, it was not possible to find a unique combination for parameters b and t_{eq} to match the experimental data, due to the same linear curve obtained for both experiments (lower and higher flow rate). What is observed, both for *Houska* and *SMT* models is that, for this fluid (with the particularity of its experiments), due to its apparent weak thixotropic effects and higher inlet pressures involved (in relation to its yield stress), no delay time is observed and the experiments fit with practically the same combinations for the constitutive parameters.

To check if the range investigated in Figure 87 represents a correct order of magnitude for these parameters, the combinations of b and t_{eq} that are representing the end points of the curve will be used to perform the comparison for the another two experiments (intermediate flow rates) as shown in Table 9.

An interesting thing to observe is the monotonic behavior for the results of the sensitivity analysis performed with the *SMT* restart parameters b and t_{eq} , when compared with the experimental data, which is clearly presented in Figure 88 (lower flow rate) and Figure 89 (higher flow rate).

Figure 88 – Delay time and stabilization time – Measured x simulated data Laponite 0.0005% (*SMT* model – lower flow rate)

It is possible to see how far are the values obtained for delay time and its respective stabilization time for each combination of b and t_{eq} , from the values observed for the experimental data. For lower values of b and higher values for t_{eq} , further is the point from the experimental data (red square point) and some superposition is observed for each increment step of b .

Figure 89 – Delay time and stabilization time – Measured x simulated data Laponite 0.0005% (*SMT* model – higher flow rate)

Results for the intermediate flow rates

The next plots (Figure 90 and Figure 91) will present the comparison between the experimental and simulated data for intermediate flow rates, considering at the simulations the combinations for parameters b and t_{eq} that represent the end points of the curve with linear tendency, presented in Figure 87. These combinations are in bold in Table 14.

Table 14 – Combinations of parameters b and t_{eq} that allowed the fit of the simulated results to the experimental data (for the lower and the higher flowrates)

teq	b
0.05	0.05
0.1	0.1
0.5	0.5
1.0	1.0
1.5	1.5

Figure 90 – Verification of adjusted parameters b and t_{eq} for the intermediate flow rate (14.0 mL/s) – SMT model

Figure 91 – Verification of adjusted parameters b and t_{eq} for the intermediate flow rate (16.1 mL/s) – *SMT* model

In both figures above it is possible to observe the expected behavior, from a physical point of view, at the first seconds of simulation. The concordance is reasonable good between the simulated and the experimental curves. The both simulated curves are also very similar, being the combination for $b = 0.05$ and $t_{eq} = 0.05$ a little bit closer to the experimental curve.

4.3.1.2. Velocity profiles evaluation

The velocity profiles measured for each experiment listed in Table 9 are presented now, comparing with respective velocity profiles obtained by simulation (for combinations of parameters b and t_{eq} that fit the experimental data using *SMT* model). The velocity profiles are presented in a normalized form to facilitate the visualization.

Considering a short time to restart the flow for these experiments, three moments were considered to compare simulated data with experimental data, referred to stabilization time (T_s): $T_s/4$, $T_s/2$ and T_s .

It is possible to observe a very good concordance between the measured and the simulated data, for all the flow rates evaluated. The velocity profiles were checked with terms of mean velocity, considering the calculation of the integral for experimental data, for comparison with the mean velocity obtained by the measured data (measured flow divided by the pipeline area). For this case, the maximum difference obtained was about 3%.

The shape of velocity profiles is according to the expectation, considering that, for this fluid, the evaluated experiments considered inlet pressures relatively far away from the minimum pressure (associated to the yield stress) to start the fluid displacement; because of this, the plug region of the profile is practically not observed (very small region), being as observed for laminar flows.

Lower flow rate (8.7 mL/s)

Figure 92 – Measured data [32] x simulated data*
 (*SMT model for b and m combinations presented in Table 14)

Intermediate flow rate (14.0 mL/s)

Figure 93 – Measured data [32] x simulated data*
 (*SMT model for b and m combinations presented in Table 14)

Intermediate flow rate (16.1 mL/s)

Figure 94 – Measured data [32] x simulated data*
 (*SMT model for b and m combinations presented in Table 14)

Higher flow rate (18.3 mL/s)

Figure 95 – Measured data [32] x simulated data*
 (*SMT model for b and m combinations presented in Table 14)

4.3.2.

Simulations for case 3 (Laponite 0.005% of salt concentration)

Following the same procedure performed for this fluid considering the *Houska* model concept, in this section will be presented the simulated results using *SMT* model, for each combination of the parameters b and t_{eq} , comparing with experimental data for all the flow rates investigated, according to the Table 11.

4.3.2.1.

Parameters influence during the restart

It was performed a sensitivity analysis for the parameters t_{eq} and b , as mentioned before (see Table 13), keeping constant the build-up parameter a , in order to evaluate in which conditions these parameters fit to the experimental data. The next items present the simulation results considering each of these combinations between both parameters (b and t_{eq}) in the λ evolution equation ($d\lambda/dt$), comparing with the experimental data measured at the laboratory.

Sensitivity to parameters b and t_{eq}

The next figures present the comparison between the experimental data and the results obtained by simulation regarding to the main restart characteristics (delay time and time to reach the steady state conditions).

Results for the lower flow rate

Figure 96 – Sensitivity analysis for parameter b ($t_{eq} = 0.1$) – Lower flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 97 – Sensitivity analysis for parameter b ($t_{eq} = 0.5$) – Lower flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 98 – Sensitivity analysis for parameter b ($t_{eq} = 1.0$) – Lower flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 99 – Sensitivity analysis for parameter b ($t_{eq} = 1.5$) – Lower flow rate
Experimental data [32] x Simulated data (*SMT* model)

Results for the higher flow rate

Figure 100 – Sensitivity analysis for parameter b ($t_{eq} = 0.1$) - Higher flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 101 – Sensitivity analysis for parameter b ($t_{eq} = 0.5$) - Higher flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 102 – Sensitivity analysis for parameter b ($t_{eq} = 1.0$) - Higher flow rate
Experimental data [32] x Simulated data (*SMT* model)

Figure 103 – Sensitivity analysis for parameter b ($t_{eq} = 1.5$) - Higher flow rate
Experimental data [32] x Simulated data (*SMT* model)

Evaluation of the sensitivity analysis

As seen in case 2 of *SMT* model (laponite with 0.005% of salt concentration), the figures above show that the delay time is more sensitive to variation for parameter t_{eq} than the variation for parameter b . On the other hand, the steps considered for its values in the evaluated matrix (Table 13) is much higher (0.5) than that considered for parameter b (0.02).

Thereafter, we believe that both parameter b and t_{eq} have some importance in *SMT* model in terms of impact on delay time (T_d), when a sensitivity analysis is considered.

It was observed, for both lower and higher flow rates evaluation, a linear tendency formed by combinations between the parameters b and t_{eq} (used as input at the simulation, in the constitutive equation for $d\lambda/dt$), that fit with a very good concordance, the experimental data with the simulated data.

As commented for the other fluid, the relationship between parameters b and t_{eq} is still intuitive, since that if the breakdown term is being increased, the parameter t_{eq} must be increase to match the same data (same flow rate), because higher is t_{eq} , longer is the time to restart and stabilize the flow.

Contrary to what happened with the other fluid, each experiment generated a different linear tendency for the combinations of parameters b and t_{eq} that fit the experimental data. Both curves are presented in Figure 104.

Figure 104 – Behavior curves for b and t_{eq} combinations that fit the experimental data (for higher and lower flow rate cases) – *SMT* model

To verify the restart requirements (delay time and the stabilization time) for the intermediate flow rates, it was considered the combination for parameters b and t_{eq} that represent the intersection between these two curves (see the following Table 15), based on the regressions equations highlighted in the figure above.

The monotonic behavior for the results of the sensitivity analysis performed with the *SMT* restart parameters b and t_{eq} , when compared with the experimental data, is one more time presented but now for the fluid with the higher yield stress, according to Figure 105 (lower flow rate) and Figure 106 (higher flow rate).

It is possible to see how far are the values obtained for delay time and its respective stabilization time for each combination of b and t_{eq} from the values observed for the experimental data.

For the experiment of lower flow rate (Figure 105), the experimental data is out of the curve probably because the inlet pressure was maintained a little bit higher, at the beginning of the experiment, than the final stabilized inlet pressure. So, we believe that this aspect delayed the final stabilization time for the simulation (it was considered at the simulation a constant inlet pressure, at the lower value stabilized, observed during the experiment).

Figure 105 – Delay time and stabilization time – Measured x simulated data Laponite 0.005% (SMT model – lower flow rate)

Figure 106 – Delay time and stabilization time – Measured x simulated data Laponite 0.005% (SMT model – higher flow rate)

Results for the intermediate flow rates

The Table 15 presents the combinations of parameters b and t_{eq} that fit the simulated data with the experimental data, for each experiment evaluated (higher and lower flow rates), regarding to the performed sensitivity analysis for these parameters. In this table is also presented the combination for parameters b and t_{eq} that represent the intersection between the curves of Figure 104 ($t_{eq} = 0.46$ and $b = 0.008$).

Table 15 – Combinations of parameters b and t_{eq} that allowed the fit of the simulated results to the experimental data (for the lower and the higher flowrates)

Lower rate		Higher rate	
t_{eq}	b	t_{eq}	b
0.1	0.000	0.1	0.001
0.5	0.008	0.5	0.010
1.0	0.013	1.0	0.032
1.5	0.017	1.5	0.055
$t_{eq} = 0.46$ and $b = 0.008$			

To check if the range investigated in Figure 104 represents a correct order of magnitude for these parameters, the combination for $t_{eq} = 0.46$ and $b = 0.008$ was considered as input to obtain the simulation results for the intermediate flow rates, presented in the next two plots.

Figure 107 – Verification of adjusted parameters b and t_{eq} for the intermediate flow rate (22.5 mL/s) – SMT model

Figure 108 – Verification of adjusted parameters b and t_{eq} for the intermediate flow rate (32.4 mL/s) – *SMT* model

This case for a fluid with a stronger thixotropic behavior using the *SMT* model helps to see clearly that is possible to obtain more deterministic results for the combination between the constitutive parameters b and t_{eq} that allows the fit between the experimental and the simulated data.

It is fundamental to evaluate flow rates that represent inlet pressures close to the minimum pressure to start the flow. This region of investigation can capture differences regarding to the constitutive parameters evaluation on the restart process.

4.3.2.2. Velocity profiles evaluation

The same behavior observed for this fluid using *Houska* model is repeated considering now the *SMT* model.

The velocity profiles simulated considering *SMT* model (for combinations of parameters b and t_{eq} that fit the experimental data) are now presented for all the experiments evaluated for laponite with 0.005% of salt concentration, comparing with the measured velocity profiles. The velocity profiles are presented in a normalized form to facilitate the visualization.

Considering a time a little bit longer to restart the flow for these experiments, four moments were considered to compare simulated data with experimental data, referred to stabilization time (T_s): $T_s/4$, $T_s/2$, $3T_s/4$ and T_s .

It is possible to observe a very good concordance between the measured and the simulated data, for all the flow rates evaluated. The velocity profiles were checked with terms of mean velocity, considering the calculation of the integral for experimental data, for comparison with the mean velocity obtained by the measured data (measured flow divided by the pipeline area). For this case, the maximum difference obtained was about 5%.

The shape of velocity profiles is according to the expectation, considering that, for this fluid, the evaluated experiments considered inlet pressures relatively near the minimum pressure (associated to the yield stress) to start the fluid displacement; because of this, the plug region of the profile is significant (fluid with higher yield stress, although considered higher flow rates).

Lower flow rate (13.2 mL/s)

Figure 109 – Measured data [32] x simulated data*
 (*SMT model for b and m combinations presented in Table 15)

Intermediate flow rate (22.5 mL/s)

Figure 110 – Measured data [32] x simulated data*
 (*SMT model for b and m combinations presented in Table 15)

Intermediate flow rate (32.4 mL/s)

Figure 111 – Measured data [32] x simulated data*
 (*SMT model for b and m combinations presented in Table 15)

Higher flow rate (35.6 mL/s)

Figure 112 – Measured data [32] x simulated data*
 (*SMT model for b and m combinations presented in Table 15)

In general, a good concordance is observed between the measured and simulated velocity profiles.

When the flow rate is increased, some difference is observed at the edges of the velocity profiles, which can be explained by the treatment of the experimental data. In these cases, it was observed some inefficiency in the velocities measurement, due to reflection effects observed locally at the experimental apparatus.

4.4. General evaluation

Based on the results presented, is possible to propose a methodology to obtain the parameters of the constitutive equation for $d\lambda/dt$, for both thixotropy models evaluated, using experimental data measured under a controlled environment (well known boundary conditions), since the experiments performing must focus on restart issues. The methodology involves the following steps and precautions:

- 1) It is necessary the evaluation of restart considering different steps for applied pressure at the inlet of the pipe. Greater the number of steps more confident will be the adjustment to obtain the parameters of the models. It is important in this process to ensure the repeatability of the measurements for each step of pressure.
- 2) Other important point is the fluid characterization, that will be even better the greater is the number of flow curve points (different pairs of τ and $\dot{\gamma}$ values in steady state conditions).
- 3) To obtain good results for the adjustment of the parameters is fundamental the evaluation of inlet pressures near (just above and just below) of the minimum pressure to start the flow, i. e. the pressure associated to the yield stress of the fluid (that overcomes the stresses at the pipeline wall). It allows to obtain more information regarding the delay time to start the flow, a parameter that is fundamental to evaluate the thixotropy effects.
- 4) Paying attention to all these aspects, it is possible to obtain different combinations for *Houska* and *SMT* parameters that, when used as input in the simulator, generate results that fit the experimental data. It is quite logical to observe that, for each experiment evaluated (for a specific inlet pressure applied), will exist infinite combinations that will promote the fit of the simulation data with measured data.

- 5) On the other hand, when this exercise is done for different inlet pressures, it is also expected that will exist only one point (combination for b and m – *Houska* model – or b and t_{eq} – *SMT* model) that will allow the fit between simulated and measured data simultaneously for all the inlet pressures analyzed, for a specific fluid.

In this work, it was possible to obtain a single combination for b and t_{eq} (*SMT* model) only for the fluid with higher yield stress value. Probably it is explained by the effect mentioned on the step 3 above. For the fluid with lower yield stress value, the inlet pressures evaluated were quite far from that one associated to its yield stress.

This single combination could not be found using *Houska* model (parameters b and m) for the fluid with higher yield stress value because an intrinsic issue of the constitutive equation for $d\lambda/dt$ for this model, which is commented in item 4.2.2.1. It is expected the increase of the unstructuring rate with the increase of shear rate. However, in this model is observed the inversion of this behavior (decrease of the unstructuring rate with increase of the shear rate), for very low shear rates ($\dot{\gamma} < 1$).

This methodology constitutes a typical example of the inverse problem, according to the literature.

5 Conclusions and final remarks

5.1. Conclusions

Considering the main objective of this work, that is the evaluation of the relationship between the parameters variation of the constitutive equations for *Houska* and *SMT* models (dimensionless values of b , m and the equilibrium time t_{eq}) and their representativeness in the simulation results, when compared to the experimental data, some aspects must be highlighted:

- these parameters are very sensitive to any variation; it means that is necessary a significant quantity of experimental data to give confidence to this kind of sensitivity analysis.

In this context, it is very important to perform experiments for inlet pressures very close to the minimum pressure to start-up the flow. It is observed that the analysis becomes more precisely in these situations, because the delay time is well defined (longer) and it can be a good guiding for the sensitive analysis.

- it is possible to estimate the parameters of the constitutive equation for $d\lambda/dt$ in a controlled environment, performing only experiments focusing on restart characteristics with a good repeatability, since the boundary conditions and the fluids characterization are well known. In this work, a methodology (inverse problem) is proposed to obtain these parameters based on the experimental data and simulation results comparison.
- the *Houska* model does not favor the restart predictability in terms of determining the values of the restart parameters of the model. Due to the non-monotonic behavior of its equation for structure evolution ($d\lambda/dt$), with the increase of the shear rate values (change of behavior for very low and for higher shear rates), the results obtained for the simulation when these parameters are varied are not intuitive.
- the *SMT* model presents a monotonic behavior for the results of the simulations, when the values of the parameters are increased or decreased,

showing an intuitive response to these variations, in terms of delay time and stabilization time.

- the velocity profiles simulated fit very well with the experimental data, considering both *Houska* and *SMT* models, for intermediate or steady-state flow rate conditions.

5.2. Final remarks

Based on the results evaluated in this work, some studies can be proposed in order to go on the investigation about the thixotropic effects for waxy crude oils, which are listed below:

- perform the sensitivity analysis simulations considering the data available from other concentrations of salt in laponite, in order to obtain different responses for the thixotropic behavior, increasing the yield stress range of investigation. The objective is identify patterns of behavior between the restart parameters evaluated.
- extend the sensitivity analysis simulations considering the effects due to the thermal and mechanical history of the flow, using real data from the field, comparing with laboratory measurements for parameters b and m (*Houska*), and b and t_{eq} (*SMT*).
- extend the analysis considering the compressibility effects during the restart process. Evaluate if this effect is significant or not to influence the delay times to start the flow.

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