THermoHydraulic Modeling in Transient State for Evaluation of Pipeline Shutdown and Restart Procedures

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ABSTRACT
In order to study shutdown and re-start in heavy crude oil pipelines, a model was developed. It simulates, in a transient state, the behavior of pressure, flow and temperature variables, averaged over the cross-sectional area and as a function of time and the axial coordinate. The model was validated with actual operational data from a test case. Results obtained for different operating points, stopping time, crude properties, topographies and lengths are presented. Additionally, the governing equations are converted to dimensionless expressions in order to obtain the dimensionless numbers relevant to the re-start operation for crude oil pipelines.

KEYWORDS / PALABRAS CLAVE
Heavy crude | Pipeline | Correlations | Extra-Heavy crude | Light crude | Viscosity | Re-start | Transient state | Modeling | Simulation | Crudos pesados | Oleoducto | Correlaciones | Crudos extrapesados | Crudos livianos | Viscosidad | Re-arranque | Estado transitorio | Modelado | Simulación

RESUMEN
Con el objeto de modelar situaciones de parada y re arranque en oleoductos que transportan crudos pesados, se desarrolló un modelo que simula, en un estado transitorio el comportamiento de las variables de presión, flujo y temperatura, promediadas en el área transversal y en función del tiempo y de la coordenada axial. El modelo fue validado con datos operacionales reales de un caso de prueba. Se presentan resultados obtenidos para diferentes puntos de operación, tiempo de parada, propiedades del crudo, topografías y longitudes. Además, las ecuaciones gobernantes se convierten en expresiones adimensionales para obtener los números adimensionales relevantes para la operación de re-arranque de oleoductos.

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1. INTRODUCTION

Simplified models for transient flow in pipes have been developed from the equations used to study transient phenomena such as water hammer [1], which models consist of expressions of mass conservation, momentum and energy for average properties in the cross-sectional area for a compressible fluid, as is proposed in [2, 9]. Transient two-dimensional models, such as the one proposed in [5, 10, 14], can provide important understanding regarding the behavior of paraffinic crudes in restart situations as a function of friction factor. Therefore, this contribution is important in what regards computational cost associated to spatial discretization procedures makes the analysis impractical in cases where pipe length is much greater than the diameter. In those situations, a one-dimensional approach is sufficient to capture relevant aspects of transient heavy crude flow (4). For instance, estimation of the inlet pressure that starts up the flow or determination of the maximum pressure for an imposed inlet flow rate (15).

Davidsen et al. [2] developed a algebraic model based on control volumes to model the behavior of paraffinic crudes in restart situations with water or oil injection, based on the model designed by Cheng et al. [3] which improves formulations developed in [11, 12] by including compressibility and time dependent Bingham constitutive equations. The authors find that the viscoplastic behavior of the crude is a determining factor in restart and restoration time of operational conditions. Vinay et al. [4] solves differential and one-dimensional mass and momentum balances for incompressible and viscoplastic fluid (Bingham Plastic). The model developed is based on a two-dimensional model for barely compressible and viscoplastic flow [5]. The authors state that the use of one-dimensional models is more appropriate for applied cases, considering the aspect ratio of the pipes and the computation times. In addition to establishing relevant dimensionless numbers for the restart of crude oils, Vinay et al. [4] solve mass and momentum balances, finding stabilization times for important scales: compressible diffusion proportional to the dimensionless compressibility ($\beta^*$), acoustic propagation proportional to the product of $\beta^*$ and Reynolds number ($Re$) and viscous damping proportional to $Re$. With a similar model but reducing dimensionality to a 1-D model, Alfamendy et al. [10] obtain results as accurate as the two-dimensional case, reducing computational time by an order of the 20 case. De Oliviera et al. [16] solve the aforementioned equations using the finite volume method, as proposed by Patankar [25], to describe the behavior of paraffinic (viscoplastic) crude in restart situations as a function of the dimensionless numbers $Re$, $\beta^*$, aspect ratio ($\beta$), dimensionless gravity and dimensionless viscosity, concluding that with a lower $Re$, the time of restoration is greater, low values of $\beta^*$ produce greater oscillations in the pressure increasing the restoration time, and the dissipation of the pressure peaks is higher in horizontal tubes than vertical. Using a similar numerical method, Sun et al. [37] compare different rheological models for heavy crude oil emulsions, concluding that the model proposed by Teng and Zhang [38] is more appropriate (4). Li et al. [7] include the energy conservation equation in a one-dimensional differential model of transient flow in pipes based on the mathematics of fluids of type [11]. By means of the characteristics method, the authors find restoration times of operational conditions, taking into account the thermal scale, which is significantly higher than the scales mentioned above, where only thermal effects are considered. Based on this methodology, Li et al. [39] developed a computational tool to predict temperature drop after shutdown and pressure and flow rate during restart.

The model used to obtain the results presented in this article is made up of the partial equations presented by Li et al. [7]. Although this model does not consider the viscoplastic behavior of paraffinic crude, it can be used as a first approximation to the transient behavior of non-isothermal heavy crudes, since the variation of viscosity in terms of temperature is considered by the friction factor. Therefore, the main contribution of this paper is the implementation of a thermohydraulic model to simulate transient fluid flow and heat transfer in heavy crude pipelines considering the fact that, to the best of the authors’ knowledge, numerical results for heavy crude pipe flow regarding velocity, pressure and temperature have not been obtained. Recent research on heavy crude fluid dynamics is mainly focused on experimental thermal shrinkage [22], friction reduction [23] and rheological behavior in terms of additive concentration [23].24] water cut [25] or a lighter crude content [26]. The proposed model could include non-Newtonian behavior, thermal shrinkage and temperature dependency of transport properties. The work is focused on introducing a modeling methodology to simulate heavy crude pipe flow, widening the applicability of the model implemented in [7].

In the next section, an explanation is provided regarding the model implemented in [1] and Ahmadpour et al. [19]. Based on the conservation equations of mass, momentum and energy in the transient state simulation and, in other equations, thermodynamic properties, both in this and in the other equations, are considered constant at a reference temperature. The overall heat transfer coefficient ($\alpha$) is obtained by an analysis of equivalent thermal resistance in the crude-pipe-soil system, considering the conductivities of each material and the conduction resistance between the pipe and the ground.

2. THEORETICAL FRAME

Based on the differential balances in terms of average quantities in the cross-sectional area of the pipe, it is possible to obtain a mathematical model whose solution represents the behavior of relevant variables in time and axial direction (2). The mass conservation equation expresses the balance of mass for pressure ($P$) and the average velocity in the axial direction ($\bar{v}$) according to equation (1), considering the compressibility effects of crude, whose rate change of volume is very small compared with the volume exhibited by the crude oil in stop conditions, giving the cooling (4).

$$\frac{\partial P}{\partial t} + \frac{\partial \bar{v}}{\partial x} \frac{1}{\rho} \frac{\partial \rho}{\partial x} = 0$$  

The linear momentum conservation equation (2) includes terms of inertia, compression, friction and gravity. The effect of the viscosity of the crude oil is given by the coefficient of friction, which is also found as a function of the radius ($R$), the density ($\rho$), the dynamic viscosity ($\mu$) and the Reynolds number ($Re$) according to the Colebrook-White equation. Friction factor is related to temperature by means of the Reynolds number, which is a function of viscosity. Another dimensionless exponential equation is used to describe viscosity behavior in terms of temperature. The angle of inclination of the pipe ($\gamma$) is found by interpolation of the pipe’s topographic data, which is part of the input data for transient state simulation and, in general, can change with the distance along the pipe z.

The conservation of energy in the crude inside the pipeline is given by the equation (3), which includes terms of enthalpy ($\mathcal{h}$), variation of enthalpy in terms of temperature ($T$), compressibility, viscous dissipation and heat loss by walls. For simplicity, the thermodynamic properties, both in this and in the other equations, are considered constant at a reference temperature. The overall heat transfer coefficient ($\alpha$) is obtained by an analysis of equivalent thermal resistance in the crude-pipe-soil system, considering the conductivities of each material and the conduction resistance between the pipe and the ground.

$$\frac{\partial}{\partial t} \left( \rho \mathcal{h} \right) + \frac{\partial}{\partial x} \left( \rho \mathcal{h} \bar{v} ight) = q_w + q_{av}$$  

The initial conditions correspond to a crude oil at rest ($\mathcal{h}(x,0)=0$), brought under the hydrostatic pressure as a function of the relative height ($h$).

$$\mathcal{h}(x,0)=h_0 - z_i$$  

The initial temperature distribution will be an input function to the model and defined according to the stop time. Two types of boundary conditions can be imposed for velocity and pressure. The first corresponds to input pressure, i.e. $p(L,t)=p_{in}$; $p(L,t)=p_{in}$.

This condition is applied in the case that one wishes to know the behavior of the velocity in time and the operation flow rate in a steady state. The second possibility is a known operational flow condition (Q): $\mathcal{h}(L,t)=\mathcal{h}_0$. This condition, together with the output pressure condition (6), is used to ascertain the transient behavior of the pressure in the restart process, as well as its maximum value and steady state. Considering the hyperbolic and non-linear nature of the system of governing equations and the characteristics of finite differences (MacCormack-type, explicit second order) is used for their spatial and temporal discretization. This numerical scheme is a two-step method with a first-order correction, which allows the determination of velocity, pressure and temperature are found from previous (or initial) values. The second step (corrector) uses the intermediate variable values in order to obtain a better approximation and complete time step calculations. More details about the method employed can be found in (21).

DIMENSIONLESS NUMBERS

It is possible to obtain a group of dimensionless numbers from the conservation equations (1-3) according to the methodology to simulate heavy crude pipeline flow, widening the applicability of the model implemented in [7]. However, this work is focused on introducing a modeling methodology to simulate heavy crude pipe flow, widening the applicability of the model implemented in [7]. For the second case (known operating flow), the characteristic velocity can be expressed as the average steady state velocity of $u_{av}$.

$$W_e = \frac{P_{in}^2 R^2}{\mu L}$$  

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From mass conservation equation, two dimensionless parameters are obtained, the aspect ratio of the pipe ($\beta$) and the dimensionless compressibility ($\beta^*$) which can be expressed, respectively, as:

$$\delta = \frac{R}{L}$$  

$$\beta^* = \frac{\rho_0}{\rho_{av}}$$  

The dimensionless momentum conservation equation is a function of Reynolds and Froude Numbers:

$$Re = \frac{\rho_{av} \bar{v} L}{\mu}$$  

$$Fr = \frac{\bar{v} L}{\sqrt{g}}$$  

The average height difference can be evaluated approximately as $\Delta h = Re - 1$. It is important to note that, in this context, the Froude number must be considered in a similarity analysis. Another important dimensionless number related to the momentum is the Reynolds number, which is the ratio of inertial and viscous forces. However, for this case, the Reynolds number, and the relative roughness of the pipe, given by:

$$\epsilon = \frac{e}{\delta}$$  

Therefore, assuming similarity of Re and $\Delta h$ will result in the same value of the friction factor. Considering the equation for the dimensionless conservation of thermal energy, it is possible to obtain a modified Eckert number ($Ee$) since it is not in terms of the temperature of the surrounding environment but in terms of the temperature of the crude outlet ($T_0$). The Eckert number establishes a relationship between the kinetic energy of the stream and the change of internal energy in the pipeline and is given by equation (15). Additionally, a relationship is obtained between the heat transferred from the crude oil and the specific heat thereof. Knowing a constant number ($\beta$), equation (18).

$$Ee = \frac{u_{av}^2}{C_p(T_0 - T)}$$  

$$U_{av} = \frac{u_{av}}{C_p(T_0 - T)}$$  

Finally, it is possible to express the conversion of thermal energy by compression/expansion in terms of a relationship between properties of the oil identified in this document, as a relationship

$$\frac{u_{av}^2}{C_p(T_0 - T)}$$  

$$\frac{u_{av}^2}{C_p(T_0 - T)}$$
The reference case corresponds to a pipeline section with a length of 84 km, an external diameter of 24 in. and an average internal radius of 0.0018 in. An initial temperature distribution is assumed, given by the cooling of the pipeline at a stop in a lapse of 72 hours.

First, results are obtained for the case of known pressure at the pipeline inlet. From the results, two time scales can be differentiated. The first corresponds to the development or restoration of flow, which occurs, in this case, in a time less than 200 seconds. In this period, one sees propagation of the wave originating by the injection of crude oil at high pressure, setting the oil in motion along the pipeline, as can be seen from the pressure and flow profiles presented in Figure 1, where they show the distributions every 20 seconds. The small disturbances observed in the graphs are more related to the usage of a second-order numerical scheme when travelling waves are present, which is the case at small intervals of time after the restart operation.

The increase in temperature along the pipeline causes a decrease in viscosity, which in turn causes a decrease in local pressure differences and an increase in operating flow, as can be seen in the graphs presented in Figure 4. In Figure 1, it is possible to observe that both the pressure and the flow rate after 200s are far from the reference data, indicated in the dotted graphs. After 40 hours, the steady state of the system is reached and the pressure and temperature are very close to the reference points (Figure 3). Figure 4 shows that, for time after restart, having appreciable changes in temperature depends on the position in the pipeline. For instance, at x=4L, a time close to 10 hours is needed to reach a temperature variation near to 50°F. The use of constant properties such as density, isothermal compressibility, thermal expansion and the heat capacity of the crude and the thermal conductivity of wall and floor, cause an error in the results that is reflected in the reference quantities, which in the case of the flow can reach up to 20% relative error. However, the solution procedure used can be employed for the comparative analysis of transient behavior in stop and restart situations for heavy oil pipelines.

For the sake of brevity, the results obtained for the case of known flow boundary conditions are not presented since the values in the steady state are analogous to those obtained for the first case, taking into account that the differences with respect to the reference data fall on the pressure values. Results found by changing, among other parameters, operation volumetric flow rate, crude quality (viscosity and density) and pipe length, are shown below. For the simulation of cases, a boundary condition for flow rate operation was established. The parameters that do not vary in the simulated cases are presented in Table 1 as input data. Among these, there are geometric aspects such as the diameter, roughness, thickness and burial distance of the pipeline, environmental conditions such as air temperature, properties such as thermal conductivities of the pipe and the ground, and operational data such as the departure pressure and stop time; the latter defines the initial temperature distribution along the pipe.
According to the results presented in Table 3, the hydraulic restoration time is inversely proportional to the flow rate, i.e. the higher the flow rate, the shorter the hydraulic restitution time. In the case of the steady state time, the flow shows a similar relationship that is affected by the variation of other properties such as the kinematic viscosity of the crude, the initial temperature and the length of the pipeline. The maximum pressure that is reported in the simulation during the re-start is proportional to the operational flow and the length of the pipeline. Regarding the percentage of friction reduction, it is clear that similar maximum pressures are obtained, and hydraulic and steady-state restoration times are obtained for flow rates that differ by a percentage similar to the percentage of friction reduction; (compare cases 1 and 2, 3, 4, 5, 6, and 7, and 8, etc.). Since different parameters are varied in different cases, relationships between the other properties can be obtained by comparing results in terms of numbers and dimensionless variables.

Table 1. General conditions cases

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Table 2. Specific data for each simulated case

According to the results presented in Table 3, the hydraulic restoration time is inversely proportional to the flow rate, i.e. the higher the flow rate, the shorter the hydraulic restitution time. In the case of the steady state time, the flow shows a similar relationship that is affected by the variation of other properties such as the kinematic viscosity of the crude, the initial temperature and the length of the pipeline. The maximum pressure that is reported in the simulation during the re-start is proportional to the operational flow and the length of the pipeline. Regarding the percentage of friction reduction, it is clear that similar maximum pressures are obtained, and hydraulic and steady-state restoration times are obtained for flow rates that differ by a percentage similar to the percentage of friction reduction; (compare cases 1 and 2, 3, 4, 5, 6, and 7, and 8, etc.). Since different parameters are varied in different cases, relationships between the other properties can be obtained by comparing results in terms of numbers and dimensionless variables.

Table 3. Results obtained for evaluated cases

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\(b\) hydraulic restart time, \(A\) steady state time, \(\rho\) maximum pressure at startup, \(\nu\) maximum pressure time, \(T_o\) crude oil outlet temperature

**REFERENCES**


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**CONCLUSIONS**

Based on the numerical solution of the one-dimensional balances of mass, momentum and energy in terms of average variables in the cross-sectional area, a calculation tool is obtained for the simulation of the oil pipeline restart process that, among other parameters, makes it possible to assert the re-start times for different operating conditions, crude properties, geometric characteristics and environmental parameters.

Results obtained by the model developed were compared with available operational data for an industrial crude oil pipeline, demonstrating good prediction of the pressure distribution and temperatures in the steady state. In the case of pressure boundary conditions, the operating flow in the steady state is underestimated with respect to the reference data, so it is necessary - for applications where greater precision in the results is required - to improve the calculation model for the friction coefficient and its relation to temperature.

Using the calculation tool, consistent results were obtained for 18 application cases in which, among other properties, flow of operation, pipe length, viscosity and density of crude oil, and injection temperature of crude oil varied. This demonstrates the versatility of the tool and its potential application in the prediction of flow behavior, pressure and temperature in re-start situations for oil pipelines. Nevertheless, future work must be focused on improving the numerical methods implemented in order to reduce overshoot for small time values and to improve transient behavior estimation.


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**NOMENCLATURE**

Re: Reynolds number

Ec*: Modified Eckert number

St: Stanton number

Fr: Froude number

RCE: crude oil compressibility and thermal expansion relationship

ρ: crude oil density (lbm/ft³)

C: crude oil specific heat (Btu/lbm/°F)

μ: crude oil dynamic viscosity (cP)

α: crude oil thermal diffusivity (ft²/s)

R: pipe radius (ft)

θ: pipe inclination angle (°)

e: pipe roghness (ft)

ε: relative pipe roughness

U: overall heat transfer coefficient (Btu/hr/ft²/F)

kt: pipe thermal conductivity (Btu/hr/ft/F)

ks: soil thermal conductivity (Btu/hr/ft/F)

T∞: ambient temperature (°F)

Ti: crude oil inlet temperature (°F)

To: crude oil outlet temperature (°F)

Pi: crude oil inlet pressure (psig)

Po: crude oil outlet pressure (psig)

tlangs: hydraulic restart time (min)

tss: stationary state time (hr)

Pstart: maximum pressure at startup (psig)

tmax: maximum pressure time (min)