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Research Paper

Transient cooling simulation of atmospheric residue during pipeline shutdowns

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HIGHLIGHTS

- CFD model solves transient heat transfer of residue during pipeline shutdowns.
- Cooling curves are predicted to estimate time allowance before full solidification.
- Pour point is used as a criterion of residue solidification.

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ABSTRACT

In this paper, a Computational Fluid Dynamics (CFD) model was developed for solving transient conjugate heat transfer of pre-heated atmospheric residue from a crude distillation unit in buried pipelines following pipeline shutdowns. The emphasis of the simulations was to predict cooling curves of the residue in a pipeline during shutdowns to help predict time allowance for operations and maintenance activities to troubleshoot the problem and resume operations before full solidification. Winter conditions were chosen to estimate duration for initiation of solidification of the residue using a criterion of pour point derived from laboratory analysis. Two different modeling approaches have been presented; axisymmetric and full pipe cross-section and both have given comparable results in estimating the residue solidification times. A scenario of energy savings by reducing initial temperature of the pre-heated residue and its impacts to the solidification time has also been presented. The results from transient CFD simulations showed cooling temperature fronts across all thermal layers including estimated time taken for the residue to reach a safe temperature margin above pour point. The model can be used as a valuable flow assurance tool to avoid the risk of residue solidification in pipelines and thus negative impact on economic resources.

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1. Introduction

Wax deposition and solidification remains a major challenge to oil and petroleum industries, ranging from damage to oil reservoir formations to blockage of pipelines and process equipment [1]. There are several driving forces that induce wax deposition in pipelines, such as the difference between the bulk oil temperature and the temperature of pipe wall or the outside temperature [2] and the hydrocarbon stream properties. When wax precipitates within pipelines at and below Wax Appearance Temperature (WAT), wax gelation starts to form and inhibit flow by causing non-Newtonian behavior and increasing viscosities as the temperature of a waxy crude oil approaches its pour point [3]. The formation of wax gelation or solid wax column during a pipeline shutdown can completely block the pipeline and could lead to major pipeline restarting problems, if insufficient pressure is available at the pipeline inlet to break the gel and allow the waxy oil to flow [4]. Problems caused by solidification and deposition of waxes during production and transportation of crude oils cost billions of dollars yearly to petroleum industry due to increasing cost of chemical wax inhibitors, production loss, well shut-in, less utilization of capacity, flow lines choking, equipment failure, extra horsepower requirement and increased manpower attention [5].

Abbreviations: CFD, Computational Fluid Dynamics; SRR, Straight Run Residue; ADR, Abu Dhabi Refinery; RR, Ruwais Refinery.

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Nomenclature

c_p	specific heat (J/kg K)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
r	radial coordinate (m)
R	pipeline radius (m)
T	temperature (K)
T_o	reference temperature (K)
t	time (s)
ρ	density (kg/m^3)
μ	viscosity (kg/m s)
μ_o	reference viscosity (kg/m s)

Subscripts

m, n	two adjacent conducting layers (between two adjacent sides of pipe wall, insulator, HDPE outer jacket, soil medium)

Preventing the wax deposition to happen in the first place is considered the most cost effective way [6]. Some prevention strategies such as use of chemical inhibitors [7,8] or combined chemical inhibitor with pigging [8] are often implemented. However, when wax deposition cannot be prevented and wax gelation starts to form and inhibits flow then wax removal strategies have to be enforced to avoid risk of full pipeline blockage. Most common practice is pigging to remove wax build-up in pipelines, sometimes in combination with chemical treatment [9]. Some heat treatment to remove wax in pipelines such as inductive heating through an external coil [10] has also been used and a preheating treatment such as injecting fresh warm oil at the pipeline entry has also been practiced to resume the flow of a compressible gel-like material [11].

Many researchers have investigated the complex process involved in wax deposition and solidification using experimental [12,13] as well as numerical approaches [5,14–17]. These studies [5,12–17] developed empirical based correlations and mathematical/numerical models describing the formation of wax deposits in a pipeline carrying waxy oil, and subjected to temperature drops due to low external temperature conditions surrounding the pipeline. Most models of wax deposition are based on molecular diffusion driven mechanism [6], although shear dispersion may play a role in wax deposit removal, which would affect the rate at which wax accumulates [18]. While the wax precipitation is mainly a function of thermodynamic variables such as composition, pressure and temperature, wax deposition is also dependent on the flow hydrodynamics, heat and mass transfer, and solid-solid and surface-solid interactions [19].

The biggest problems in waxy crude oils transportation are complete blockage of the pipelines and restarting of gelled flowlines [20]. As the rheology of waxy oils is highly temperature dependent, the heat transfer system must be considered under normal uninterrupted/steady flow operations as well as during restarting flow conditions after downtime. In fact, drastic heat transfer during shutdown makes static cooling much more problematic than dynamic cooling during uninterrupted flow [20].

Pipeline shutdowns may occur for maintenance, operational or emergency reasons [11]. Under non-flowing conditions when the pipeline is surrounded by low external temperature, the temperature in the pipeline starts to drop. This temperature decline causes the crystallization of paraffinic components eventually leading to wax gelation build-up as the temperature continues to drop below pour point. When the shutdown period extends too long the wax gel formation or solid column can completely block the pipe, and hinder restarting of the pipeline. Therefore, it is clear that the temperature is the key parameter of the whole shutdown and restart processes [17].

An early study of transient cooling in an insulated oil pipeline during shutdowns was described by Szilas [21] using an analytical model based on linear-heat-source correlations. The model assumed homogeneous soil properties, constant temperature of oil all over a certain cross-section of the pipeline including the pipeline wall cross-section and also constant heat flux around the pipeline wall. Although several simplifications of model and approximation of variables that determined the cooling rates were done, this analytical method nevertheless gave general cooling trends of waxy oil in pipeline during shutdowns.

Many numerical studies [22–24] have been conducted recently to describe the transient cooling behavior of waxy oil pipelines in non-flow condition. These studies allow prediction of temperature drop of the waxy oil during shutdowns and generation of temperature profiles along both radial and axial directions. Evaluation of the temperature drop during such events makes prediction of wax solidification time also possible [24].

Cheng et al. [22] employed a two-dimensional Finite Volume Method (FVM) to discretize the governing equations with an unstructured grid. Soil was represented as a finite thermal influence region and assumed to be homogeneous and isotropic. Their mathematical model, however, required an artificial heat coefficient to represent natural convection of the crude oil in the same way as considered in conduction. Furthermore, their numerical model used a stagnation point concept by dividing the pipeline into liquid and solid regions and the layer of wax deposit on the pipeline wall was assumed uniformly distributed along the entire pipeline.

Lu and Wang [24] developed a two-dimensional FVM based heat transfer model covering phase changes both in water-saturated soil around the pipeline and in crude oil inside the pipeline during pipeline hindrances in winter. An axially symmetrical boundary condition was used by assuming negligible heat transfer in the axial direction of the pipeline. Fixed physical boundaries/interfaces had to be implemented explicitly to represent different regions in the soil based on the phase state of water, i.e. frozen soil, freezing soil, and water saturated soil and also three regions representing the crude oil in pipeline, i.e. solidified oil, solidifying oil and liquid oil.

Han et al. [23] adopted a different approach with a Proper Orthogonal Decomposition (POD) Galerkin reduced-order model (ROM) for solving unsteady heat conduction problems of oil pipeline. Using body-fitted coordinate and a similar heat influence region approach of Cheng et al. [22] the model resulted in more efficient and faster computational time. Assumptions such as negligible heat transfer in the axial direction of pipeline and use of equivalent heat coefficient to represent natural convection of the crude oil still needed to be made. However, just like its predecessor, the POD reduced-order model also used pre-defined layer of wax, i.e. fixed segregated liquid and solid regions.

The physical phenomena surrounding the solidification of waxy oil in pipeline during shutdown are highly complex involving wax crystal formation, wax deposition near the pipeline wall, wax gelation with yield-stress plastic rheology, and phase changing with

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