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Research Paper

Numerical investigation of waxy crude oil paste melting on an inner overhead pipe wall

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ABSTRACT

This paper presents a transient numerical study of melting waxy crude oil block paste on an inner overhead pipe wall at different water temperatures and flow rates. Computations are based on an iterative, finite-volume numerical procedure that incorporates enthalpy–porosity technology to simulate the phase change phenomenon. Temperature variations, liquid frictions, and temperature field structures at variable monitoring points were investigated. Results show that the initial temperature distributions is U-shaped along the monitoring line, with temperature decreasing gradually from the free surface of the oil to its interface with the pipe wall. The flow pattern has a significant influence on the melting time in its transition from laminar to turbulent, but has little effect after the transition. These results provide a reference for the hydraulic suspension transport process in waxy crude oil pipelines.

1. Introduction

Because of its high solidification point, high viscosity, and high wax content, known collectively as the "three highs" of crude oil in China, the temperature of waxy crude oil at a well head is often lower than its solidification point when the amount of liquid produced from an oil well is low, or when the length travelled in a pipe is long. Therefore, the technology for mixing the oil with hot water has been used widely when gathering and transferring crude oil. However, the produced oil cannot be melted quickly with hot water, thus clogging pipes and causing oil well shutdowns [1,2].

The phase change process for crude oil includes crystallization and melting. Research on the crystallization process of waxy crude oil in pipe shutdowns has developed rapidly [3–5]. Tommy et al. [6] utilized FLUENT software to study the unsteady heat transfer process of atmospheric residue with a high pour point. They discussed the impact of reducing the initial inlet axial straight run residue (SRR) temperature to SSR solidification time during buried pipeline shutdowns in peak winter conditions. Zhao [7] applied the method of combining traditional finite element analysis with a curvelet transform to study temperature change rules and solidification times of crude oil in different regions of a seabed pipeline. Liu et al. [8] adopted the partition allocation method to establish the shutdown temperature drop mode of an aerial hot oil pipe using FLUENT software. They obtained temperature distributions and solid–liquid interface variations considering natural convection. Lu and Wang [9] developed a two-dimensional finite volume method (FVM) based on a heat transfer model covering phase changes both in water-saturated soil around a pipeline and in crude oil inside the pipeline during a pipeline shutdown in winter. Fixed physical boundaries/interfaces had to be implemented explicitly in order to represent three regions in crude oil, i.e., solidified oil, solidifying oil, and liquid oil. An axially symmetrical boundary condition was used by assuming negligible heat transfer in the axial direction of the pipeline. Du et al. [10] simulated the crude oil temperature drop rule by using the enthalpy–porosity technology and determined the position of the erstarrung zone, dilution zone, and liquid oil zone at different times. Xu et al. [11] employed two-dimensional FVM to construct a mathematical model for a buried hot crude oil pipeline during shutdown. The model required an artificial heat coefficient to represent natural convection of the crude oil in the same way as in conduction and used a stagnation point concept by dividing the pipeline into liquid and solid regions.

The above literatures focused on temperature distributions and total solidification time with different boundary conditions in the crystallization process of crude oil during a pipeline shutdown. However, studies of the melting process of waxy crude oil block paste on the inner overhead pipe wall have been very limited, and this relevant research has an important influence on the transportation of crude oil mixed with water.

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Nomenclature

C	empirical model constant
c_p	specific heat (J/kg K)
F	body force (kg m/s^2)
G	turbulent kinetic energy production term (J)
H	enthalpy (J/kg)
h'	heat transfer coefficient
P	pressure (Pa)
q	heat flux (W/m^2)
T	temperature (K)
$\vec{u}$	velocity component (m/s)

Greek symbols

ρ	density (kg/m^3)
τ	time (s)
η	dynamic viscosity (kg/m s)
λ	thermal conductivity (W/m K)
ε	turbulent kinetic energy dissipation rate
$\sigma_k/\sigma_\varepsilon$	turbulent Prandtl numbers
γ	liquid fraction
∇	hamiltonian operator
μ_t	turbulent viscosity (kg/m s)
k	turbulent kinetic energy (J)

Subscripts

a	air
ini	initial time
L	liquid phase
o	oil
p	pipeline
ref	reference value
S	solid phase
w	water

The flow structure of crude oil depends on the state of the wax, and the problem of melting oil can be summarized as a problem of melting wax in oil, which is an unsteady heat transfer problem with a phase change [12,13]. Existing knowledge regarding melting wax and other phase change materials (PCM) is very mature [14–19].

Some scholars have studied the melting characteristics of PCM using computational fluid dynamics (CFD) in rigid shells such as spheres and rectangles. Karunesh et al. [20] studied the performance of five different fatty acids when used with two-dimensional rectangular containers. They concluded that capric acid took the minimum time for melting and solidifying under the same conditions. Hosseinizadeh et al. [21] and Assis et al. [22] numerically explored the process of melting a PCM in spherical geometry. They exposed the top of the simulation cell to accommodate a significant increase in PCM volume during the solid–liquid phase transition. The above studies provide a reference for establishing a model of melting for crude oil in pipelines.

In an attempt to improve the heat transfer performance of PCMs, Ye et al. [23], Nourouddin et al. [24], and Yang et al. [25] set fins on the plate and internal walls of the simulation cells. They studied the impact of the number of fins, the fin length, and the fin thickness on the melting process. The numerical results of Dhaidan et al. [26] and Nourouddin et al. [27] showed that the heating rate in the eccentric condition was faster than in the concentric condition in the melting process of PCMs, which was due to the high rate of temperature fluctuations and thermal instabilities in the eccentric condition.

The ice slurry heat transfer process in a flow can be described as forced convection heat transfer of a non-Newtonian fluid subject to a phase change (i.e., the melting of ice crystals). Yan et al. [28] studied the heat transfer characteristics of ice slurry in a straight horizontal tube using of the volume-of-fluid (VOF) model in CFD software. Beata [29] applied the enthalpy–porosity method to model the melting process that occurs during the homogenous tube flow of an ice slurry. Kalaiselvam et al. [30] studied the heat transfer and pressure drop characteristics of a tube–fin heat exchanger in an ice slurry HVAC system. The numerical analysis concluded that the ice slurry HVAC system resulted in a 7.4% increase in the temperature drop compared with a conventional chilled water system. Kousksou et al. [31] used differential scanning calorimetry (DSC) to understand the non-isothermal melting kinetics in an ice slurry, and simulation results showed that the temperature gradients inside the sample were a dominating factor. Generally, analyses of flow and heat transfer characteristics of ice slurries are similar to those for crude oil in a pipeline.

This study investigates the melting process of crude oil paste on an inner pipe wall using CFD. Additionally, the phase change temperatures of the oil used in the presented numerical simulations range widely. The affect of the water temperature and flow state on temperature variations and melting time are described. Details of computational procedures are discussed in the following sections.

2. Methods and materials

2.1. Physical model

The flow pattern of the liquid produced by mixing oil with water and a schematic of the simplified model are shown in Figs. 1 and 2, respectively. The pipeline is a cylinder 53 mm in inner diameter, 1000 mm in length, and 2 mm in wall thickness. The crude oil is an arched block having a length of 50 mm, a maximum radial height of 10 mm, and a volume of 14,447 mm^3. The coordinates of points A and B are (625, 16.5, 0) and (625, 26.5, 0), respectively, and the monitoring point C is the midpoint of line AB. During the melting process, hot water flowed through the pipeline and melted the crude oil. In the simulations, the heat was convected from the hot water to the oil and was conducted within the oil block.

Fig. 1. Flow pattern of the liquid produced by mixing oil with water.