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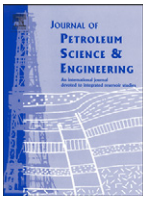

Research paper

# Numerical analysis of the heat transfer associated with freezing/solidifying phase changes for a pipeline filled with crude oil in soil saturated with water during pipeline shutdown in winter

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ABSTRACT

A flow and heat transfer model for a crude oil pipeline buried in soil saturated with water during shutdown, where ambient temperature is below the freezing point of water, has been established. Phase changes involving water freezing in the soil and crude oil solidifying in the pipeline and the influence of initial temperature and flow field were included in the model, and the natural convection of water in soil and crude oil in the pipeline were also taken into account. Temperature and flow fields, and interfaces of water freezing in soil and crude oil solidifying in the pipeline were obtained through numerical simulation. Numerical results show that the temperature gradient in the soil is greatest near the top of pipeline, and that natural convection of water and oil occurs from bottom to top along a vertical symmetrical line in both soil and pipeline due to the temperature distribution. The freezing interface for water in soil and solidification interface of oil in the pipeline advance to greater depths with increasing time of shutdown. The rate of increase in the depth of the freezing interface is slower in the soil near the top of the pipeline than in that far from the pipeline.

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## 1. Introduction

Buried pipelines are widely used for transporting fluids in a variety of applications such as water distribution networks, oil pipelines, power plant steam lines, and heat exchangers in soil thermal energy storage systems. Engineering design of systems of this type has to take into account the heat transfer between the soil and the buried pipeline, which in many cases has a significant impact on both economics and safety. Heat losses from oil pipelines transporting viscous fluids result in increasing viscosity of the fluid due to the reduction in fluid temperature, leading to increased pump power consumption. In water-saturated soil, the problem of heat transfer is complicated by the need to consider phase change processes occurring in both the soil around the outer surface of the pipeline and in the pipeline itself, especially when pipeline has to be shut down in winter whether because of an accident or for scheduled maintenance. In such situations, it is of critical importance to know both the temperature distributions and how the phase change fronts advance in the water-saturated soil and in the crude oil inside the pipeline.

Many studies of the heat transfer associated with phase changes occurring around a pipeline, inside a pipeline, or in porous media have been reported. In the case of heat transfer associated with phase changes occurring in the region around a pipeline, solidification studies around a single cylinder have been conducted by Bathelt and Viskanta (1980) and Cheng et al. (1988), as well as melting/solidifying studies around two or more cylinders completed by Bathelt et al. (1979), Sasaguchi and Viskanta (1987), Sasaguchi and Viskanta (1989), and Lacroix (1993). Mathematical modeling of the thermal interactions between a pipeline carrying oil or gas and frozen soil under steady-state and non steady-state conditions has also been described by Bronfenbrener (1980), Furman (1981), and Hastaoglu and Hakin (1996). Hastaoglu and Hakin (1996) used string-intersected boundaries combined with three-level alternating-direction implicit finite-differential techniques to solve a three-dimensional transient partial differential equation model of heat transfer from a buried pipe in frozen soil. The model enables the time needed for the temperature of the fluid flowing in the buried pipe to fall to its freezing point to be predicted. In many cases reported by Seshadri and Krishnayya (1980), Lunardini (1981), Sadegh et al. (1987), and Bronfenbrener and Korin (1999), the approximate quasi-steady approach can provide a fast and simple solution, with acceptable accuracy for practical engineering purposes. Bronfenbrener and Korin (1999) proposed an approximate two-dimensional theoretical model based on a quasi-steady approach for thermal analysis of phase change processes around an insulated pipeline buried horizontally in semi-infinite frozen soil. The model was verified by comparison with numerical and other approximate solutions in the literature. The theoretical results show that the propagation of the thawing/freezing interface is limited under constant boundary conditions. The reverse process occurring as a result of interruption of the fluid flow was also examined. Based on the solution for prediction of the boundary location of the thawing region, an analytical equation for

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**Nomenclature**

| | |
|---|---|
| $a$ | Convection heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |
| $c$ | Specific heat (J kg$^{-1}$ K$^{-1}$) |
| $C$ | Coefficient in the Ergun modification of Darcy law |
| Const | Constant (J kg$^{-1}$) |
| $D$ | Diameter (m) |
| $f$ | Liquid fraction |
| $g$ | Gravitational constant (m s$^{-2}$) |
| $h$ | Depth of buried pipeline (m) |
| $H$ | Enthalpy (J kg$^{-1}$) |
| $K$ | Permeability (m$^2$) |
| $l$ | Equivalent dimension (m) |
| $L$ | Latent heat (J kg$^{-1}$) |
| $Lx$, $Ly$ | Length of rectangle (m) |
| $P$ | Pressure (Pa) |
| $Ra$ | Rayleigh number |
| $t$ | Time (s) |
| $T$ | Temperature (K) |
| $u$ | velocity (m s$^{-1}$) |
| $x$ | coordinate axes (m) |
| $y$ | coordinate axes (m) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | Thermal diffusivity (m$^2$ s$^{-1}$) |
| $\beta$ | Coefficient of volume expansion (K$^{-1}$) |
| $\phi$ | Property such as density or specific heat |
| $\varphi$ | Porosity |
| $\lambda$ | Thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $\mu$ | Dynamic viscosity (kg m$^{-1}$ s$^{-1}$) |
| $\nu$ | Kinematic viscosity (m$^2$ s$^{-1}$) |
| $\rho$ | Density (kg m$^{-3}$) |

*Subscripts*

| | |
|---|---|
| a | Ambient |
| $j$ | The $j$th layer in pipeline |
| l | Liquid |
| liq | Liquidus |
| n | Outer surface of pipeline |
| o | Crude oil |
| p | Phase change material such as water or crude oil |
| ref | Reference |
| s | Solid |
| sld | Solidus |
| w | Water |
| 0 | Inner surface of pipeline |

determination of the fluid temperature as a function of time was developed. Ismail and da Silva (2003) have described a numerical study of the melting of phase change materials around a horizontal circular cylinder with constant wall temperature in the presence of natural convection in the melt region. A two-dimensional mathematical model was formulated in terms of primitive variables and a coordinate transformation technique was used to fix the moving front.

Furthermore, heat transfer associated with phase changes taking place inside the pipeline must also be considered. The problem of heat transfer from horizontal tubes where freezing is taking place at the inner walls has been the subject of considerable attention. The form of the ice growth that occurs in a pipeline where the fluid flow is initially in transition and turbulent regimes was investigated by Gilpin (1981), and Hirata and Mutsuzawa (1987). Their experimental studies revealed that the ice thickness under these flow conditions was not stable. They concluded that the transient freezing process depends strongly on both the flow and the temperature conditions. Negiz et al. (1993) and Hastaoglu et al. (1995) described the numerical procedures necessary to solve the transient three-dimensional equations that describe heat transfer from a fluid in laminar flow inside a buried pipeline to the soil, when the top soil surface undergoes a sudden decrease in temperature.

Heat transfer associated with phase changes is also significant in porous media. Lacroix (1993) proposed a numerical model for analyzing phase change heat transfer around two cylinders in a rectangular cavity and numerically simulated cyclic melting and resolidification of a paraffin wax, a system which had been previously studied experimentally by Sasaguchi and Viskanta (1989). A stream function–vorticity formulation was employed by Lacroix (1993), however, and it is difficult to determine the vorticity at the solid–liquid interface with such a model. Moreover, this model cannot be used to treat the solid/liquid phase change heat transfer processes occurring in porous media such as soil. A numerical model has been proposed by Bennon and Incropera (1987), and Sasaguchi and Takeo (1994) for simulation of the solid–liquid phase change heat transfer in water-saturated porous media confined in a rectangular cavity using primitive variables—velocity, pressure and temperature. Sasaguchi et al. (1997) proposed a numerical model for analysis of solid–liquid phase change heat transfer in systems with a complex geometry which can be used for solid/liquid phase change heat transfer as well as conventional transient natural convection, in the presence or absence of porous media. Bau (1984) analyzed the steady-state heat transfer from a pipeline buried in a semi-infinite porous medium, where the pipeline wall and the top surface of the porous medium are assigned constant temperatures and the mechanism for heat transfer is natural convection within the medium.

In some of the reported mathematical models, assumptions such as constant wall temperature, constant heat flux around the pipeline surface, or heat transfer occurring solely by conduction, have been made for the purposes of simplification. Martinez and Beaubouef (1972) assumed constant wall temperature, did not consider conductive resistance in the surrounding media, such as the soil or the pipe wall, and dealt with variations in two dimensions only. Three-dimensional phase change problems have been studied by Hastaoglu (1987), and Gilmore and Guceri (1988). In fact, the transient heat transfer problem when there is freezing occurring in both soils saturated by water and in the pipeline because the ambient temperature is below the freezing points of water and crude oil, involves complex mechanisms of flow and transfer. It cannot be assumed that the pipe wall temperature is constant or that there is a constant heat flux across the pipe wall.

There have been a large number of studies of heat transfer associated with phase changes based on the assumption that conduction is the sole mode of heat transfer. The presence of natural convection during melting may lead to an increased rate of heat transfer however and lead to unrealistic predictions. A pioneering study by Sparrow et al. (1977) of fusion around a vertical cylinder showed that natural convection cannot be ignored in the analysis of solidification processes. Later Yao and Chen (1980) obtained an approximate solution for the problem of solidification around a horizontal cylinder with constant temperature by using the perturbation technique. They studied the effect of natural convection on the solidification process and concluded that it depends strongly on the Rayleigh number. In many subsequent studies conducted by Yao and Cherney (1981), Rieger et al. (1982), Prusa and Yao (1984a), and Prusa and Yao (1984b), the influence of natural convection on the process of solidification around a horizontal cylinder has been taken into account.

In essence there are two methods of formulating the problem of heat transfer associated with phase changes. The first uses temperature as the dependent variable in the energy equation while the second uses enthalpy as the dependent variable. In the former case, the energy equation is written separately for each phase and coupling between the two equations is achieved by means of energy balance at the solid–liquid interface. In this type of formulation it is necessary to know explicitly the position of the interface in order to determine the temperature. Having a

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