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Study on the restart algorithm for a buried hot oil pipeline based on wavelet collocation method

Qing Yuan [a], Bo Yu [b,*], Jingfa Li [b], Dongxu Han [b], Wenhua Zhang [a]

[a] National Engineering Laboratory for Pipeline Safety, Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum, Beijing 102249, China

[b] School of Mechanical Engineering, Beijing Key Laboratory of Pipeline Critical Technology and Equipment for Deepwater Oil & Gas Development, Beijing Institute of Petrochemical Technology, Beijing 102617, China

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ABSTRACT

The influence of soil temperature field on the restart process of crude oil pipeline is not considered in previous studies. However, it cannot be ignored for the long-time restart of buried hot oil pipeline. Considering the long computation time for the solution of soil temperature field, the study on the hydraulic-thermal coupled acceleration algorithm for the restart process of buried hot oil pipeline is conducted. Firstly, the mathematical models considering the influence of soil temperature field are introduced in detail for the restart problem. Then based on wavelet collocation method, the adaptive gird is generated to reduce the computational cost of soil temperature field. Furthermore, the hydraulic-thermal coupled acceleration algorithm is proposed, which can realize the fast coupled solution of the restart process. Finally, the optimal values of threshold and coarsest level of resolution are investigated for the restart problem, and the time-adaptive strategy and no-time-adaptive strategy are compared. And the conclusions are drawn from the comparison and analysis of numerical results, which can provide beneficial guidance to the choices of threshold, coarsest level of resolution and adaptive strategy in future studies.

1. Introduction

In modern petroleum industry, the pipeline is the main conveyance of crude oil. Some kinds of crude oil are highly viscous (heavy oil) or exhibit high wax precipitation rate (waxy crude oil) [1] under the natural ambient temperature, which show poor fluidity. For the sake of improving the fluidity of these kinds of crude oil, they are generally heated when transported [2]. However, the pipeline inevitably encounters shutdown because of regular maintenance or occasional emergency. When the shutdown occurs, the temperature of crude oil drops gradually and the fluidity becomes poorer with the increase of shutdown time. If the shutdown time is too long, the poor fluidity of crude oil may induce the failure of restart and cannot ensure the safety of operation (especially for waxy crude oil). Therefore, the safe restart of oil pipeline is a significant problem for the field operation.

Accurate description or simulation of restart process is an important but challenging task in petroleum industry. Over the past two decades, there have been several efforts for the study on the restart problem. Based on a three-yield-stress model, Chang et al. [3] researched isothermal restart of pipeline transporting incompressible crude oil. It was found that the yield stress and time-dependent rheology of the gelled oil played an important role in determining the flow rate after restart, and the accuracy of simulation critically depended on a complete knowledge of the rheological behavior of gelled oil. On basis of the research in [3], Davidson et al. [4] presented a restart model which took into account the compressibility and longitudinal variations in physical and rheological properties of two fluids. They pointed out that the compressibility effectively caused an increase in the final flow rate and a decrease in the clearance time. But the Davidson model (and Chang model) assumed that the gel broke down with time rather than with strain, and thus it is difficult to extend the validity of the Davidson model (and Chang model) predictions [5]. Vinay et al. [6] proposed the 2D model which consisted of three conservation equations and a constitutive equation, and presented a decoupled algorithm to solve velocity, pressure and temperature. Moreover, the influence of wall temperature changes on restart process was investigated. But in this Vinay model, the rheological state is assumed to be constant, and thus the rheological breakdown of the gel cannot be captured in the restart process. Considering the compressibility of crude oil was ignored in [6], Vinay et al. [7] investigated the influence of compressibility on the basis

* Corresponding author.
E-mail address: yubobox@vip.163.com (B. Yu).

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Nomenclature

Roman symbols

a	Pressure wave speed ($m \cdot s^{-1}$)
a_E, a_{EN}, a_{ES}, a_N, a_P, a_S, a_W, a_{WN}, a_{WS}	Coefficients of nine-diagonal discretized equations
A_0, A_1, A_2	Coefficients of the performance curve of pump
b	Source term of nine-diagonal discretized equations
b_0	Source term of five-diagonal discretized equations
c_I	Specific heat capacity of the Ith layer, including wax deposition layer, steel pipe wall, anticorrosive coating, insulating layer and soil ($J \cdot kg^{-1} \cdot {}^\circ C^{-1}$)
c_p	Specific heat capacity of crude oil ($J \cdot kg^{-1} \cdot {}^\circ C^{-1}$)
c_{start}	Specific heat capacity of crude oil at the start of pipeline ($J \cdot kg^{-1} \cdot {}^\circ C^{-1}$)
d	Effective inner diameter of pipeline (m)
E	Elastic modulus of pipeline (Pa)
f	Fanning friction factor
$\bar{f}$	Average fanning friction factor
g	Gravity acceleration ($m \cdot s^{-2}$)
Gr_{av}	Grashof number under the average temperature of crude oil and pipe inner wall
Gr_o	Grashof number under the crude oil temperature
h	Height of computational domain for the cross-section (m)
h_0	Buried depth of pipeline (m)
H	Pressure head (m)
H_{atm}	Pressure head corresponding to the atmospheric pressure (m)
H_{end}	Pressure head at the end of pipeline (m)
H_{pump}	Lift of pump (m)
H_{set}	Set pressure head (m)
H_{start}	Pressure head at the start of pipeline (m)
$\bar{H}$	Average pressure head (m)
i, j, k	Serial numbers of grid nodes in horizontal, vertical and axial directions respectively
K, L, M	Three serial numbers
K_o	Volume elasticity coefficient of crude oil (Pa)
l	Length of computational domain for the cross-section (m)
m	Time layer of thermal computation
n	Time layer of hydraulic computation
nb	Serial number of upwind node neighboring kth node on adaptive grid
n_e	Time layer of hydraulic computation corresponding to the mth time layer of thermal computation
n_s	Time layer of hydraulic computation corresponding to the (m-1)th time layer of thermal computation
N	Grid number on uniform grid
N_c	Grid number on adaptive grid
N_{heat}	Total amount of the working furnaces of heating station
N_{pump}	Total amount of the working pumps of pumping station
N_ξ	Total amount of scaling function coefficients
N_ζ	Total amount of wavelet coefficients
Pr_{av}	Prandtl number under the average temperature of crude oil and pipe inner wall
Pr_o	Prandtl number under the crude oil temperature
Pr_w	Prandtl number under the temperature of pipe inner wall
q	Heat flux density from crude oil to surroundings ($W \cdot m^{-2}$)
q'	Heat flux density from crude oil to cross-section ($W \cdot m^{-2}$)
Q_{start}	Flow rate at the start of pipeline ($m^3 \cdot s^{-1}$)
r	Serial number of the level of resolution
r_o	Radial coordinate (m)
R	Level of resolution
R_c	Coarsest level of resolution
Re	Reynolds number
s	Transportation distance (m)
t	Time coordinate of restart process (s)
t_c	Computation time of CPU (s)
T	Generalized soil temperature (°C)
T_a	Temperature of the atmosphere (°C)
T_c	Temperature of the soil at the constant temperature layer (°C)
T_s	Temperature of the seawater (°C)
T_w	Temperature of wax deposition layer or steel pipe at the pipe inner wall (°C)
v	Axial velocity of crude oil ($m \cdot s^{-1}$)
v_a	Average wind speed at the ground surface ($m \cdot s^{-1}$)
$\bar{v}$	Average axial velocity of crude oil ($m \cdot s^{-1}$)
W	Power of heating furnace ($J \cdot s^{-1}$)
x	Horizontal coordinate (m)
y	Vertical coordinate (m)
z	Axial coordinate (m)

Greek symbols

α_a	Convective heat-transfer coefficient of air at the ground surface ($W \cdot m^{-2} \cdot {}^\circ C^{-1}$)
α_o	Convective heat-transfer coefficient of crude oil at the pipe inner wall ($W \cdot m^{-2} \cdot {}^\circ C^{-1}$)
β_o	Expansion coefficient of crude oil
Γ	Set including all serial numbers of wavelet coefficients
δ_c	Speedup ratio
$\delta_{\Delta z}$	Ratio of the minimum spatial step of adaptive grid and the spatial step of uniform grid
$\delta_{\Delta t}$	Ratio of the time steps corresponding to adaptive grid and uniform grid
Δ	Thickness of steel pipe wall (m)
Δt_v	Time step of hydraulic computation (s)
Δt_Θ	Time step of thermal computation (s)
$\Delta z^{\mathrm{grid1}}$	Spatial step of uniform grid (m)
$\Delta z^{\mathrm{grid3}}$	Spatial step of adaptive grid (m)
$\Delta\Theta_{heat}$	Temperature increase of crude oil through a heating furnace (°C)
ε_e	Unified error precision of five-diagonal and nine-diagonal discretized equations
ε_{e1}	Error precision of five-diagonal discretized equations
ε_{e2}	Error precision of nine-diagonal discretized equations
ε_s	A small value guaranteeing computational stability
ε_w	Prescribed threshold
ζ	Wavelet coefficient for the crude oil temperature
$\zeta'_{i,j}$	Wavelet coefficient for the node temperature of cross-section
η	Efficiency of heating furnace
Θ	Crude oil temperature (°C)
Θ_{inlet}	Crude oil temperature at the inlet of station (°C)
Θ_{start}	Crude oil temperature at the start of pipeline (°C)
λ_{av}	Thermal conductivity of crude oil under the average temperature of crude oil and pipe inner wall ($W \cdot m^{-1} \cdot {}^\circ C^{-1}$)
λ_I	Thermal conductivity of the Ith layer, including wax deposition layer, steel pipe wall, anticorrosive coating, insulating layer and soil ($W \cdot m^{-1} \cdot {}^\circ C^{-1}$)
λ_o	Thermal conductivity of crude oil under the temperature of crude oil ($W \cdot m^{-1} \cdot {}^\circ C^{-1}$)
μ	Dynamic viscosity of crude oil ($Pa \cdot s$)
ξ	Scaling function coefficient for the crude oil temperature
$\xi'_{i,j}$	Scaling function coefficient for the node temperature of cross-section