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Study on the thermal characteristics of crude oil batch pipelining with differential outlet temperature and inconstant flow rate

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ABSTRACT

When several kinds of crude oil need to be transported, the batch pipelining is a better choice than the "single-pipeline-single-oil" and blending pipelining due to its advantages. In the batch pipelining process, to avoid the frequent operations on the pumps and control valves, the flow rate is generally inconstant in practice. All previous studies simplify the flow rate distribution as a constant one, which largely deviates from the engineering practice. Focused on this point, based on the features of the batch pipelining in practice, the gradient-type flow rate distribution model and corresponding calculation approach are proposed in this paper. The accuracy of this model and corresponding calculation approach are verified by the field data, and it indicates that the accuracy of numerical results can meet the engineering requirement. Further, the thermal characteristics of the batch pipelining are found by numerical simulation and the further analysis is carried out to make these characteristics more convincing. Finally, the shortcoming of the step-type flow rate distribution with simple expression is pointed out. It is found that the adoption of the step-type flow rate distribution in the simulation would introduce a prominent deviation when the change period of flow rate is relatively long. To overcome this shortcoming, the proposed gradient-type flow rate distribution, whose accuracy is higher, is an alternative method.

1. Introduction

In the modern petroleum industry, pipelining keeps the major approach for the transportation of the crude oil. In the situation that several kinds of crude oil are planned to be transported, if the "single-pipeline-single-oil" transportation strategy is adopted, several pipelines should be constructed, which requires a high cost of construction investment and is obviously uneconomic. If these kinds of crude oil can be transported in a single pipeline, the economic efficiency can be largely improved. The blending pipelining is the easiest approach to realize the "single-pipeline-multiple-oil" transportation strategy. However, if the physical properties of these kinds of crude oil differ significantly from each other, this strategy will cause big problems. On the one hand, the physical properties of the blending oil are unstable because of the inevitable amount fluctuation of different kinds of crude oil from upstream pipelines or oil fields. This brings difficulties to the processing of refineries because they are sensitive to the properties of the crude oil. On the other hand, the blending oil lowers the quality of the crude oil with good fluidity, and some products may not be able to be refined, for example, lubricating oil (Wang et al., 2013).

The batch pipelining is combined with separated refinement and separated storage for different kinds of crude oil, and can overcome the shortcomings of the blending pipelining as mentioned above. In the batch pipelining, the crude oil with poor fluidity (high-viscosity oil) should be heated and the crude oil with good fluidity (low-viscosity oil) should be kept unheated or slightly heated. During the transportation, the heated crude oil keeps transferring heat to the environment (mostly the surrounding soil) while the unheated (or slightly heated) crude oil absorbs heat from the environment. Thus, the thermal characteristics are much higher complex than the conventional pipelining process.

The batch pipelining with differential outlet temperature was first applied to the Pacific Pipeline System, which was situated at California U.S. and commissioned in 1999 (Mchugh and Hanks, 1998; Mecham et al., 2000a, 2000b; Shauers et al., 2000). Five kinds of oil with different

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Nomenclature

Roman symbols

A	Cross-section area of the crude oil pipeline (m^2)
c_k	Specific heat capacity of the kth layer, including wax deposition layer, steel pipe wall, anticorrosive coating, insulating layer and soil (J/(kg·°C))
c_p	Specific heat capacity of the crude oil (J/(kg·°C))
c_{p1}	Specific heat capacity of the low-viscosity oil (J/(kg·°C))
c_{p2}	Specific heat capacity of the high-viscosity oil (J/(kg·°C))
d	Effective inner diameter of the pipeline (m)
d_{in}	Inner diameter of the steel pipe (m)
e	Energy of the crude oil (J/kg)
f	Darcy friction coefficient
g	Gravity acceleration (m/s^2)
h	Specific enthalpy of the crude oil (J/kg)
H	Height of the thermal-influenced region of the pipeline (m)
H_0	Buried depth of the pipeline (m)
L	Length of the thermal-influenced region of the pipeline (m)
L_0	Length of the pipeline (m)
n	Serial numbers of the batches
p	Pressure of the crude oil in the pipeline (Pa)
q	Heat flux density from the crude oil to the surroundings (W/m^2)
q_e	Absorbed heat of the crude oil from overcoming expansion of the fluid (J/kg)
q_f	Frictional heat of the crude oil from the flow of the fluid (J/kg)
q_s	Absorbed heat of the crude oil from the soil (J/kg)
q_{sum}	The sum of the absorbed heat of the crude oil (J/kg)
Q	Flow rate of the low-viscosity oil or high-viscosity oil (m^3/s)
Q_{a1}	Average flow rate of the low-viscosity oil (m^3/s)
Q_{a2}	Average flow rate of the high-viscosity oil (m^3/s)
Q_g	Flow rate of the low-viscosity oil or high-viscosity oil for the gradient-type flow rate distribution (m^3/s)
Q_m	Flow rate of the low-viscosity oil or high-viscosity oil for the step-type flow rate distribution (m^3/s)
Q_{s1}	Flow rate in the stable period of flow rate of the low-viscosity oil (m^3/s)
Q_{s2}	Flow rate in the stable period of flow rate of the high-viscosity oil (m^3/s)
$\overline{Q}_1$	Average flow rate of the low-viscosity oil in the pipelining process (m^3/s)
$\overline{Q}_2$	Average flow rate of the high-viscosity oil in the pipelining process (m^3/s)
s	Height difference of the axial direction of the pipeline (m)
t	Transportation time (s)
t_1	Total transportation time of a single batch for the low-viscosity oil (s)
t_2	Total transportation time of a single batch for the high-viscosity oil (s)
t_{c1}	Total transportation time of the change period of flow rate within a single batch for the low-viscosity oil (s)
t_{c2}	Total transportation time of the change period of flow rate within a single batch for the high-viscosity oil (s)
t_m	Total migration time of the crude oil (s)
t_{m1}	Total migration time of the low-viscosity oil head (s)
t_{m2}	Total migration time of the high-viscosity oil head (s)
t_{s1}	Total transportation time of the stable period of flow rate within a single batch for the low-viscosity oil (s)
t_{s2}	Total transportation time of the stable period of flow rate within a single batch for the high-viscosity oil (s)
T	Temperature of the pipeline cross-section (°C)
T_a	Temperature of the atmosphere (°C)
T_c	Temperature of the soil at the constant temperature layer (°C)
u	Specific energy of the crude oil (J/kg)
v	Average velocity of the crude oil (m/s)
x	Horizontal direction (m)
y	Vertical direction (m)
z	Axial direction of the pipeline (m)

Greek symbols

$\alpha, \beta, \gamma, \delta$	Some intermediate parameters due to the coordinate transformation from the Cartesian coordinate to the body-fitted coordinate
α_a	Convective heat-transfer coefficient of the air at the ground surface ($W/(m^2 \cdot °C)$)
α_o	Convective heat-transfer coefficient of the oil stream at the wax deposition layer ($W/(m^2 \cdot °C)$)
β_o	Expansion coefficient of the crude oil ($°C^{-1}$)
Δ	Thickness of the wax deposition layer (m)
θ	Angle between the axis of the pipeline and the horizontal line
Θ	Temperature of the crude oil (°C)
Θ_{out}	Station-outlet temperature of the crude oil (°C)
Θ_s	Temperature of the crude oil at the pipeline starting point (°C)
λ_k	Thermal conductivity of the kth layer, including wax deposition layer, steel pipe wall, anticorrosive coating, insulating layer and soil (W/(m·°C))
ξ, η	Body-fitted coordinate
μ_1	Dynamic viscosity of the low-viscosity oil (Pa·s)
μ_2	Dynamic viscosity of the high-viscosity oil (Pa·s)
ρ_k	Density of the kth layer, including wax deposition layer, steel pipe wall, anticorrosive coating, insulating layer and soil (kg/m^3)
ρ_o	Density of the crude oil (kg/m^3)
ρ_{o1}	Density of the low-viscosity oil (kg/m^3)
ρ_{o2}	Density of the high-viscosity oil (kg/m^3)
φ	Time ratio of the stable period of flow rate
φ_1	Time ratio of the stable period of flow rate for the low-viscosity oil
φ_2	Time ratio of the stable period of flow rate for the high -viscosity oil
χ	Correction coefficient
χ_1	Correction coefficient of the low-viscosity oil
χ_2	Correction coefficient of the high-viscosity oil

properties were batch-pipelined, whose temperatures ranged from 18.8 °C to 82.2 °C. However, the technical details of this pipeline are hardly publicized. With the development of the batch pipelining with differential outlet temperature, some numerical studies have been conducted. Cui, X. G. et al (Cui and Zhang, 2004a; Cui, 2005). established a mathematical model to describe the unsteady hydraulic and thermal problem for the batch pipelining process. Moreover, the basic characteristics of the thermal process were acquired by the numerical simulation. Zhou, J. et al (Zhou et al., 2009). investigated the influences from pipeline length, batch number, flow rate and outlet temperature on the safety of the batch pipelining, whose thermal characteristics were summarized. Wang, K. et al (Wang et al., 2008, 2009; Wang, 2009). defined the concept of "heating timing". Heating consumptions for several heating methods were analyzed and compared. And it was