



A steady-state heat-transfer model for solids deposition from waxy mixtures in a pipeline



Samira Haj-Shafiei, Dalia Serafini, Anil K. Mehrotra *

Department of Chemical and Petroleum Engineering, University of Calgary, Calgary, Alberta T2N 1N4, Canada

HIGHLIGHTS

- We present a mathematical model for solids deposition from paraffinic mixtures in a pipeline.
- The model is based on steady-state heat-transfer considerations.
- The predicted deposit thickness increases in the hot flow regime and decreases in the cold flow regime.
- The cold flow regime involves two-phase flow with wax crystals suspended in the liquid phase.
- The modeling approach and predictions will be useful to flow assurance engineers.

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ABSTRACT

A steady-state heat-transfer model is presented for the formation of a deposit-layer from wax–solvent ‘waxy’ mixtures in a pipeline under turbulent flow. The waxy mixture is taken to enter the pipeline under the single-phase hot flow regime (where the average mixture temperature is higher than its wax appearance temperature, *WAT*) and, upon gradual cooling, the mixture transitions into the cold flow regime (where its average temperature is lower than its *WAT*). The cold flow regime is characterized by two-phase flow, in which solid particles are suspended in the liquid phase. The effect of deposit aging is incorporated via a shear-induced deformation approach proposed in the literature. The model predictions are reported for the deposit thickness, waxy mixture temperature, pressure drop and the rate of heat loss in the hot flow and cold flow regimes for a range of inlet mixture temperature, surrounding temperature, and the Reynolds number. The predicted deposit thickness is shown to increase axially in the hot flow regime, to reach a maximum as the liquid temperature approaches the *WAT* of the wax–solvent mixture, and to decrease gradually to zero in the cold flow regime. The trends in the model predictions compare satisfactorily with those reported from bench-scale experimental studies as well as the predictions from an unsteady state moving boundary problem formulation.

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1. Introduction

Crude oils are complex mixtures of hydrocarbons, which are often subjected to large temperature gradients when flowing in pipelines, particularly in subsea environments. High molecular weight paraffin waxes (with carbon number ranging from 18 to 65) are soluble in crude oil at high temperature and pressure environments such as in petroleum reservoirs [1,2]. When highly paraffinic crude oil, called “waxy” crude oils, are subjected to a colder environment, the solubility of paraffin waxes decreases, resulting in their separation from the crude oil. The separated waxy solids can precipitate, deposit and build up as wax-like

species onto the pipeline wall, which cause major operating issues for the petroleum industry. The consequences of such phenomena are flow assurance problems, including reduced process efficiencies as a result of decrease in effective pipe diameter, an increase in pressure drop, and potential temporary or permanent shutdown of the operation [3]. A further concern is the difficulty in re-starting the pipeline filled with congealed crude oil, which often requires extremely high pressures or might not even be possible [4].

The transported crude oil cools down gradually as it flows through the pipeline until it reaches the surrounding temperature. The deposition starts when the pipe-wall temperature becomes less than the crude oil’s wax appearance temperature (*WAT*), which is the temperature at which the first wax particles separate from the crude oil. The deposit forming at the pipe-wall is a gel consisting of a waxy solid network entrapping a liquid phase [2,5]. The

* Corresponding author. Tel.: +1 403 220 7406.

E-mail address: mehrotra@ucalgary.ca (A.K. Mehrotra).

Nomenclature

A_c	surface area of outer pipe wall in contact with cold surroundings (m^2)	R_o	outside pipe radius (m)
A_h	area of liquid–deposit interface (m^2)	Re	Reynolds number
A_i	inside pipe surface area (m^2)	Re_i	inlet Reynolds number
β	tilting angle of cubical cage (degree)	Δt	time interval or residence time (s)
$C_{p,l}^{mix}$ or C	wax–solvent mixture specific heat capacity (J/kg K)	T_c	surrounding temperature (K)
D	inside pipe diameter (m)	T_d	liquid–deposit interface temperature (K)
δ	deposit thickness (m)	T_h	average wax–solvent mixture temperature (K)
Δf	change in solid wax phase mass fraction	T_{hin}	inlet wax–solvent mixture temperature (K)
ΔH_m	latent heat of fusion (J/kmol)	T_{hout}	outlet wax–solvent mixture temperature (K)
q	rate of heat transfer (W)	T_L	liquidus temperature (K)
q_d	rate of heat transfer across deposit layer (W)	T_m	melting-point temperature (K)
q_h	rate of heat transfer from wax–solvent mixture (W)	T_{wi}	inside pipe wall temperature (K)
F	volumetric flow rate (m^3/s)	T_{wo}	outside pipe wall temperature (K)
g	mole fraction	T_δ	average deposit temperature (K)
h_c	convective heat transfer coefficient of coolant ($W/m^2 K$)	U_i	overall heat transfer coefficient based on inside area ($W/m^2 K$)
h_h	convective heat transfer coefficient for wax–solvent mixture ($W/m^2 K$)	V_s	solid phase volume fraction in deposit
$(\Delta H_m)_i$	enthalpy of melting or fusion for component i (J/kmol)	V_l	liquid phase volume fraction in deposit
k or k_l^{mix}	thermal conductivity of wax–solvent mixture ($W/m K$)	V_S	solid phase volume fraction in untilted cubical cage
k_d	thermal conductivity of the deposit layer ($W/m K$)	V_L	liquid phase volume fraction in untilted cubical cage
$(k_i)_i$	thermal conductivity of wax ($W/m K$)	$V_{S\beta}$	solid phase volume fraction in tilted cubical cage
$(k_i)_j$	the thermal conductivity of solvent ($W/m K$)	$V_{L\beta}$	liquid phase volume fraction in tilted cubical cage
k_m	thermal conductivity of pipe material ($W/m K$)	w_{29}	mass fraction of wax in wax–solvent mixture (mass%)
L	pipe length (m)	w_{29}^*	liquid phase mass fraction of C_{29}
ΔL	length of axial pipe element for steady state calculations (m)	w_i	mass fraction of component i (mass%)
v	molar volume ($m^3/kmol$)	x	rate of cooling ($^{\circ}C/min$)
m	mass flow rates of wax–solvent mixture (kg/s)	y	mass fraction of wax in wax–solvent mixture (mass%)
μ	viscosity of wax–solvent mixture (Pa s)	z	axial location (m)
Δp	pressure drop (Pa)	$Z_i (=z/a)$	ratio of the edge thickness to the side of the cubical cage
ρ_l^{mix}	wax–solvent mixture density (kg/m^3)	ϕ_i and ϕ_j	superficial volume fraction of paraffin wax and solvent
ρ_i	paraffin wax and solvent densities (kg/m^3)		
Pr	Prandtl number		
R	inside pipe radius (m)		

Acronyms

WAT	wax appearance temperature (K)
WPT	wax precipitation temperature (K)

compositions of solid and liquid phases in the deposit vary across the deposit layer thickness as a result of changes in shear stress (caused by the flowing crude oil), temperature, and the composition of the flowing liquid. Over time, the solid wax deposit forms a stronger continuous wax crystal network resulting in a stiffer material [6]. The gel networks have a complex morphology, and their characteristics are greatly affected by wax composition [7], process conditions (i.e., temperature, shear) [8–10], and time [6,7]. The wax deposit shows non-Newtonian characteristics compared to the crude oil, which behaves as a Newtonian fluid at temperatures higher than WAT [6,11]. A number of experimental and modeling studies have been reported on the flow and rheological behavior of the oil and wax components in crude oil [2,6,11].

In general, when a warm “waxy” crude oil (at an average temperature higher than its WAT) flows through a pipeline in a cold environment (at a temperature lower than the WAT), it may experience two flow regimes, known as hot flow and cold flow [12–14]. In the hot flow regime, the average waxy mixture or crude oil temperature is higher than the WAT, where solids deposition takes place on the pipe wall. The deposit thickness increases axially as the temperature of the waxy mixture decreases until a maximum deposit thickness occurs when the crude oil temperature approaches the WAT. The cold flow regime is considered to start when the temperature of the crude oil becomes less than the WAT, resulting in the formation of wax crystals. In this regime, the precipitated solid crystals stay in the flowing waxy mixture

(or crude oil), giving rise to a suspension and the deposit thickness decreases [12,15]. This phenomenon is an important attribute of the cold flow technology for decreasing or preventing wax deposition [13]. There are several other commercial methods considered by flow assurance groups to prevent or remediate wax deposition, including chemical additives, thermal insulation, and mechanical treatments. All of these methods have underlying shortcomings, including high costs, environmental issues and viability [7]. The development of a more precise control strategy and technology would avoid risks for offshore pipelines, including the risk of their inspection and cleaning operations [7].

The “cold flow” technology has been proposed as an alternative approach for the transportation of waxy crude oils [12,13,15]. Merino-Garcia and Corraera [13] reviewed existing patents on the methods for creating wax–oil suspension mixture for the cold flow technology. Several possible explanations have been suggested for the decreased deposition under cold flow conditions, including a lower thermal driving force between crude oil and surrounding temperature, crystallization of wax on the suspended wax particles (which act as nucleation sites), and a lowering of the wax appearance or cloud point temperature as the heavier paraffins gradually precipitate out of the solution [13]. Among these, the latter explanation suggests that, as a result of the preferential precipitation of wax constituents with higher carbon numbers, the liquid phase becomes leaner consequently with a lower WAT. It is pointed out that the suspended wax crystals in the liquid phase do not contribute to solids deposition [12,15].

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