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Numerical prediction of wax deposition in oil–gas stratified pipe flow

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ABSTRACT

Wax deposition in oil–gas two-phase pipe flow can be a significant flow assurance problem. It becomes complicated when gas phase flow is involved. In this work, a numerical model is proposed for the wax deposition for oil–gas stratified smooth pipe flow. A unidirectional flow numerical model is used to calculate the non-isothermal hydrodynamics, heat and mass transfer. The wax deposit layer is assumed to be a growing porous layer, which caused by the diffusion of wax molecules through a porous medium. The numerical calculation performance is illustrated by the lab-scale flow experiment. The model could give the non-uniformly circumferential distribution of wax deposit on the inner pipe wall, i.e. a crescent shape, and the predicted deposit thickness is shown to increase with an increasing in superficial gas velocity and superficial oil velocity. The trends in the model predictions compare satisfactorily with those from lab-scale experimental results. In addition, it was found that the concave-down configuration of the oil–gas interface must be taken into accounted for the wax deposit. Unfortunately, this has not been taken into account in all previous studies.

1. Introduction

Wax deposition in subsea oil pipelines is a significant flow assurance problems, because it can cause a blockage and restriction in the pipelines [1–4]. The problem could become more serious especially for long subsea pipelines, as drilling moves further offshore, where the environment temperature is very cold and about 4 °C, below wax appearance temperature (WAT) [5,6]. Under the field conditions, the deposit layer formed on the pipe wall is usually removed mechanically (i.e., by pigging) [7,8]. In order to properly schedule the pigging operation, design effective remediation strategies, and mitigate the wax deposition problem properly [7,9], it is necessary to predict the deposition behavior accurately.

1.1. Wax deposition mechanism

It is known that molecular diffusion [7,10–13] and heat transfer [9,14–18] have been widely considered to be the most prevalent mechanisms for wax deposition in single phase. These two mechanisms for modeling the wax deposition involve a contradictory in treatment of the oil-deposit interface temperature. The heat transfer assumed that the oil-deposit interface temperature is equal to the WAT of the oil and remains constant during the deposit process. The is the important assumption, however it has not been validated experimentally in pipe flow without significantly interrupting the flow and heat-transfer profile. On the other hand, the molecular diffusion estimated oil-deposit interface temperature from the energy balance and it increase gradually from the inner pipe wall temperature initially to the WAT at the steady state (i.e., deposit formation stop). This increase of oil-deposit interface temperature throughout the deposit growth process is due to the insulation effect of the buildup deposit layer. Singh et al. [10] and Huang et al. [13] developed a comprehensive aging model used molecular diffusion, which describes the solid wax content in the deposit layer increasing with time.

The model allows obtaining a reasonably good agreement of deposit thickness and mean solid wax content in the deposit layer between simulated and experimented result under laboratory conditions. In practical progress, the model of Singh et al. [10] is associated with an increase in the wax solids concentration across the deposit from layer surface toward the wall. Huang et al. [13] used an evolution of the solids fraction averaged over the layer with time, and ignored the solids fraction varying across the deposit layer. Eskin et al. [7,19] assumed the deposit layer as a porous layer, and developed a mathematical description of diffusion of wax molecules through a growing porous layer, which composes porous medium, wax saturated hydrocarbon fluid. The diffusion of wax molecules through porous layer and precipitation caused

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Nomenclature

Variables

A	cross-sectional area inside the pipe (m^2)
C	wax concentration in crude oil (kg/m^3)
$D_{in,in}$	inner diameter of inner pipe (m)
$D_{in,out}$	out diameter of inner pipe (m)
D_{eff}	effective diffusivity in the deposit (m^2/s)
dP/dz	pressure gradient (Pa/m)
D_{WO}	diffusivity wax in crude oil (m^2/s)
F_w	wax fraction in the deposit (wt%)
$\overline{F}_w$	average wax fraction in the deposit (wt%)
g	gravitation (m/s^2)
H_L	liquid holdup
h_e	overall heat transfer coefficient ($W/(m^2 \cdot K)$)
h_L	liquid level for plane interface (m)
h_0	heat-transfer coefficient ($W/(m^2 \cdot K)$)
i, j, k	coordinate of mesh point at ξ, η, z coordinate direction
$J_{A,\xi}, J_{A,\eta}, J_{B,\xi}, J_{B,\eta}$	mass flux of wax molecules into the deposit ($kg\ m^{-1}\ s^{-1}$)
J_{wax}	mass flux of wax molecules from the oil to oil-deposit interface ($kg\ m^{-1} s^{-1}$)
L	length of pipe (m)
l_ξ, l_η, l_z	scale factors of bipolar coordinate system
M_{tot}	the total deposited wax mass (kg)
n	the coordinate axis normal to the layer surface
Pr	Prandtl number
Q	flow rate (m^3/s)
R	radius of pipe (m)
S	wetted perimeter (m)
Sc	Schmidt number
T	temperature (°C)
t	time (s)
V_{tot}	total volume in the closed system (m^3)
w	velocity in the axial direction (m/s)
w_{sl}	superficial liquid velocity (m/s)
w_{sg}	superficial gas velocity (m/s)
x, y, z	axial coordinate in Cartesian system (m)

Greek letters

α	the equivalent crystal aspect ratio
Γ_T	effective thermal diffusivity
Γ_w	effective viscosity (m^2/s)
Γ_C	effective mass transfer
Γ_ϕ	generalized diffusivity
γ	circumferential angle (°)
$\Delta\rho$	density difference between oil and gas (kg/m^3)
δ	deposit thickness (m)
η	coordinate in bipolar system
θ_1	upper section of the pipe wall (rad)
θ_2	the angle for interface (rad)
φ	porosity of the deposit layer
λ	heat conductivity coefficient ($W/(m \cdot K)$)
μ_m	kinematic viscosity coefficient (m^2/s)
μ_t	eddy diffusivity for momentum (m^2/s)
ξ	coordinate in bipolar system (rad)
ρ	density (kg/m^3)
σ	interfacial tension between oil and gas (N/m)
Θ	wetted wall fraction

Subscripts

bulk	properties at the bulk
dep	properties of the deposit
envir	properties of the coolant liquid.
gas	properties of the gas
i, j, k	coordinate of mesh point at ξ, η, z coordinate direction
ini	properties at initial time
inlet	properties at the inlet
inner	from bulk to the inner wall (for ξ coordinate)
int	properties at the oil–gas interface
interface	properties at the oil-deposit interface
oil	properties of the oil
odi	from bulk to the deposit (for ξ coordinate)
pipe	properties of the pipe
wall	properties at the pipe inner wall
wax	properties of the wax
water	properties of the water
ws	solubility of wax

the porosity reduction. They could give porosity distributions across normalized deposit layer thickness for different time moments. The porosity is an important characteristic of the deposit because it significantly affects the yield stress of wax deposit, which is important in the design of pigging.

1.2. Wax deposition in oil/gas flow

Most of the wax deposition studies have been focused on single-phase flow. However, production under multiphase gas–oil–water flow is normally encountered in subsea pipeline. However, up until now, there is no published study on three-phase gas–oil–water wax deposition [20]. To achieve a comprehensive three-phase wax deposition modeling, the two-phase oil–water and gas–oil wax deposition models need to be studied first. It is found that the wax deposit under multiphase flow depends on the flow pattern [3,20–23]. The deposit thickness distributions along the pipe circumference under oil–gas two-phase pipe flow is shown in Fig. 1, which is from Matzain et al. [3]. For oil–gas stratified smooth flow, only the oil-wetted pipe wall can be observed wax deposit and the deposit was distributed in a crescent shape, as shown in Fig. 1.

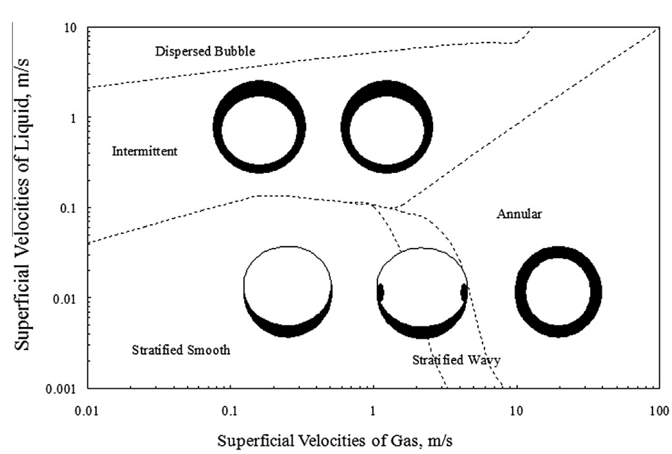

Fig. 1. Wax thickness distribution for various horizontal flow patterns [4].