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1D Numerical Simulations of Wax Deposition in a Subsea Passive Cooler Prototype for the Evaluation of Minimum Experimental Test Times

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Abstract

This paper explores a methodology for estimating the minimum duration of an experiment focusing on wax deposition studies to be carried out for a passive subsea cooler prototype geometry, upon relevant conditions for offshore oil & gas applications. The methodology encompasses 1D thermohydraulic numerical simulations of a dense-gas and waxy oil mixture flowing, as well as a mass transfer approach for the wax deposition. The idea is to obtain the minimum measurable impact of wax deposits on the pressure drop and temperature at the locations in which corresponding sensors shall be installed. The results applied to 10 different operational conditions for the cooler prototype are presented and thoroughly discussed, together with the phenomenology of the wax deposition and its relationship with the test conditions and other important flow parameters. The main conclusions and possible next steps for this work are then outlined.

Keywords

Wax Deposition; Subsea Cooler; Multiphase Flow

Introduction

The deployment of subsea coolers in offshore oil & gas production systems has three engineering purposes: (i) mitigating the structural integrity risks caused by the influence of high temperatures on materials of the wellhead assembly and flowlines, (ii) enhancing the compression efficiency of the multiphase production stream by increasing the mass flow rates capacity [1] and (iii) making it possible to pump dense gas streams by increasing the fluid density. As examples of (ii), one can mention the Gullfaks and Åsgard fields of the Norwegian continental shelf [1]. Subsea coolers can be either passive, active, or of a hybrid type (such as the sectioned or the by-pass passive coolers) [1]. The passive coolers usually include an array of coils, which take advantage of the cold subsea environment and of the formation of a natural gas buoyant plume, which enhances the heat transfer rates and the cooling efficiency of the multiphase flow. Possible issues in the maldistribution of the multiphase stream and liquid contents in the cooler header [1], incoming fluids with liquid contents higher than the design condition, the presence of cold spots, and the operation of the cooler outside its designed operational envelope can make it very exposed to flow assurance issues [1]. If the flowing stream encompasses a waxy condensate or oil, wax deposition can be a major risk that could decrease the cooler performance as well as clogging parts of the coils of the cooler manifold. Thus, investigating wax-related risks should be a priority in the design and operation of subsea coolers. Such a goal could be achieved both using numerical simulations (of the multiphase stream dynamics and wax deposition) and by performing experimental campaigns. The former, however, suffers from high uncertainties due to the modelling challenges of not only the wax deposition phenomenon, but also of the flow of the multiphase system, due to the cooler coils geometries and the complex heat transfer mechanism of the outer natural convection buoyant plume [1]. Performing experimental measurements of wax deposition is thus a necessity for the subsea cooler. The design and planning of them, nonetheless, can be supported by numerical simulations in several aspects.

The objective of this paper is thus to present a methodology that employs the results of a one-dimensional (1D) wax deposition model (henceforth called “the cooler model”) for estimating the minimum test time required for each test condition of an experimental campaign designed for investigating the wax-formation risks in a subsea cooler prototype. The latter is actually a simplified version ("scale-down") of a full-scale subsea cooler with several coils, which is under development.

The Cooler Model

The cooler model is based on the assumption that the time-scales of the wax deposition phenomenon are much larger than the time-scales of the multiphase flow that occurs in the cooler prototype. This way, the multiphase flow can be approximately interpreted as being in a steady-state in relation to the wax deposition. It is well known that transient time-scales of momentum transfer are a lot shorter than heat transfer and mass transfer, thus it can be considered a reasonable assumption by both the most accepted wax deposition mechanisms in literature: molecular diffusion and heat transfer [3]. The cooler model is composed of a gas-liquid 1D steady-state homogeneous model and by a transient wax deposition model, which are described below:

1D Steady-State Homogeneous Model

The 1D steady-state gas-liquid flow model of the cooler model is based on a modified version of the homogeneous mixture model, and can predict the profiles of the mixture velocity, mixture temperature, pressure, and volume fraction along the pipe. The solution of the governing system of equations (mixture mass, liquid mass, mixture momentum and mixture total energy conservation equations) is achieved by the finite volumes method, with the SIMPLE pressure-velocity coupling scheme, the 1st-order upwind approximation and a staggered grid for the mixture momentum equation [4]. The radial heat transfer is accounted for by the combination of the internal forced convection, the conduction in the pipe wall, and the external natural convection. A multiplier of the natural-convection Nusselt number is applied for emulating the effect of the natural convection buoyant plume on each segment of the coil. Correlations are used for the Nusselt numbers as well as for the Fanning wall friction factor of the mixture. The gas and liquid properties are extracted from pre-calculated look-up tables, such as those employed in commercial flow assurance software. The mass transfer between the phases is evaluated based on the gas equilibrium mass fractions from these tables. A correlation is employed for taking into account the extra pressure drop in the cooler prototype bends.

Transient Wax Deposition Model

The transient wax deposition model has the goal of predicting the evolution of the wax deposit thickness δ_D along the pipe, based on its volume fraction α_D, for which Eq. (1) can be written, where t is the time, ρ_D is the deposit density, A is the cross-sectional area and Γ_D is the wax mass deposition rate (in kg/m.s). The relation between α_D and δ_D is expressed in Eq. (2), where D is the internal diameter.

$$\frac{\partial(\alpha_D \rho_D A)}{\partial t} = \Gamma_D \tag{1}$$

$$\delta_D = \frac{D}{2}\left(1 - \sqrt{1 - \alpha_D}\right) \tag{2}$$

Using an explicit scheme, Eq. (1) is numerically solved and applied for all the pipe domain, and the previous solution from the steady-state flow model is used for the evaluation of Γ_D. The latter is represented by a modified version of the Matzain model [5], seen in Eq. (3), where χ_O is the oil mass fraction, ρ_O is the oil density and $\partial T/\partial r|_i$ is the radial temperature gradient at the pipe internal surface, which is expressed by Eq. (4). In it, T_i is the pipe internal wall temperature, T is the bulk temperature, k_M is the mixture thermal conductivity and η_i is the convective heat transfer coefficient at the pipe internal wall. The modifications in the Matzain model are due to the necessary units of Γ_D and due to the use of the wax mass concentration in the mixture (C_{wM}) rather than in the oil, as it is traditionally done. That was performed as mixture-based Wax Precipitation Curves (WPCs) were employed in the current model, to avoid issues due to the high CO_2 contents in the mixture, as observed in another work [6]. Moreover, the wax diffusivity $\mathcal{D}_{wo}$ was evaluated based on an updated version of the Hayduk-Minhas correlation [7]. The evaluation of the term Π_1 can be found in the literature [5] and, due to the risk of the overprediction of the shear stripping term Π_2, it was considered null in the present work: $\Pi_2 \approx 0$. Conservative estimates for the wax deposits might be obtained due to this approximation, which can be considered reasonable nonetheless for the purposes of this work.

$$\Gamma_D = \alpha_O \rho_O \pi D \left(\frac{\Pi_1}{1 + \Pi_2}\right) \mathcal{D}_{wo} \frac{1}{\chi_O} \frac{\partial C_{wM}}{\partial T} \frac{\partial T}{\partial r}\bigg|_i \tag{3}$$

$$\frac{\partial T}{\partial r}\bigg|_i = \frac{\eta_i (T_i - T)}{k_M} \tag{4}$$

The Cooler Prototype

The geometric configuration of the cooler prototype is composed by a single coil with approximately 16 horizontal segments and 180º downward bends (the inlet section is at the upper segment). Furthermore, the cooler prototype will be equipped with several sensors for the detection of the wax deposition, which includes pressure drop sensors in three segments: one near the inlet section, one in the middle of the geometry and one near the outlet section. Pressure and temperature sensors (including one at the outlet section) were positioned along the geometry for a complete monitoring of the experiments. For the latter, a dense gas and CO_2-rich mixture was employed with varying mass flow rates and low liquid (oil) contents (0.5% and 5%). Two high pressure conditions were employed (150 and 240 bar) and a fixed inlet temperature of 50°C was adopted. The experiments also encompass test-cases in which solely live oil is employed, in order to enhance wax deposition, allowing the testing of wax removal techniques (e.g. hot oil flushing, injection of chemical solvents, etc.).

Estimation of the Minimum Test Times

It is clear that for the detection of the wax deposits, the variable of interest (ϕ) must vary, due to the wax deposition, more than the uncertainty of the sensor ($\delta\phi$). The variable ϕ could be pressure drop in the segments or temperature at a certain point in the system. Thus, in order to estimate the minimum duration of an experiment for the detection of the wax deposition (τ) based on the transient signal of ϕ: (i) the difference $\Delta\phi(t)$ between the current values and the initial one (without wax) is evaluated, Eq. (5); (ii) based on the $\Delta\phi$ values, a function $\widetilde{\Delta\phi}$, Eq. (6), is calibrated so that the minimum test time can be extrapolated (a_i, $i \in \{1,2,3\}$ are tuning factors and the function format was chosen based on previous experience); and (iii) the root of $\Psi(t)$, Eq. (6) ("sf" is a safety factor), is calculated, which results in the minimum time for the detection of the wax deposition.

$$\Delta\phi(t) = \underbrace{\phi(t)}_{\text{with wax}} - \underbrace{\phi(t=0)}_{\text{no wax}} \quad (5)$$

$$\widetilde{\Delta\phi} = a_0 \ln(a_1 t + a_2)\,; a_0, a_1 \geq 0 \wedge a_2 \geq 1 \quad (6)$$

$$\Psi(t) = \widetilde{\Delta\phi}(t) - \mathrm{sf}\sqrt{2}\,\delta\phi = 0 \quad (7)$$

The transient signals of ϕ can either stem from real experimental measurements or from numerical simulations, which is the case of this work. Furthermore, if more than one parameter ϕ is used, the test times for each one is calculated and the lowest one will be the final result.

Results and Discussion

The cooler model simulations were made for 10 cases with varying gas flow rates (Q_G), LVFs (Liquid Volume Fractions) and pressures, as outlined in Tab. 1, in which $Q_{G,3} > Q_{G,2} > Q_{G,1}$ and $LVF_2 > LVF_1$. In Case 10, only oil with a small flow rate was employed, in order to maximize wax deposition. The estimated τ are already present in Tab. 1. Before discussing the estimated τ values, it is interesting to discuss the general predictions of the simulations, the deposit thickness behavior, the mixture temperature variation and how the normalized oil volume fraction change with length, these results are shown in Figs. (1)-(4) for Cases 1 and 10. In Case 1, Fig. (1) shows that the inception of the wax deposit occurs near the inlet section, indicating that its wax appearance temperature is near 50°C. Furthermore, the deposit profile is a result of the greater temperature gradients in the cooler beginning and the wax diffusivity and oil density behavior. The increasing thermal insulation and decreasing cooler efficiency due to the wax formation is observed in the temperature results for Case 1 in Fig. (2).

Table 1 – Cooler model cases and τ results.

#	Q_G	LVF	P [bar]	Estimated τ [h]
1	$Q_{G,3}$	LVF_2	240	0.51
2	$Q_{G,2}$	LVF_2	240	0.95
3	$Q_{G,1}$	LVF_2	240	1.39
4	$Q_{G,1}$	LVF_1	240	25.23
5	$Q_{G,2}$	LVF_1	240	17.34
6	$Q_{G,3}$	LVF_1	240	9.35
7	$Q_{G,3}$	LVF_1	150	1.80
8	$Q_{G,2}$	LVF_1	150	3.33
9	$Q_{G,1}$	LVF_1	150	4.08
10	0	100%	150	2.13

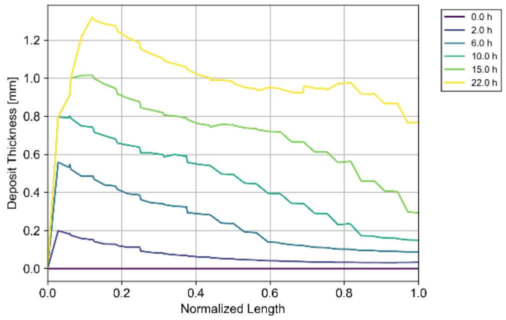

Figure 1. Deposit thickness for Case 1.

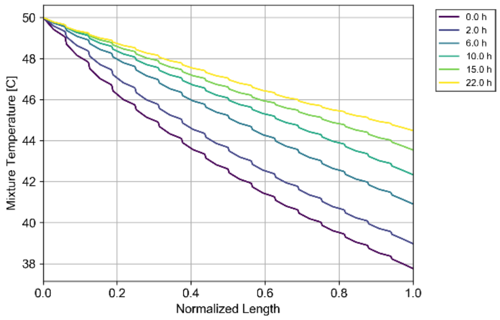

Figure 2. Mixture temperature for Case 1.

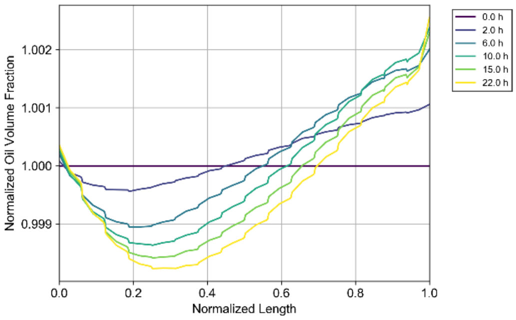

Figure 3. Oil volume fractions for Case 1.

Moreover, Fig. (3) illustrates that the oil volume fraction results indicate that a retrograde evaporation occurs followed by a slight condensation. Although not very significant, this effect references the complex phase behavior of this CO_2-rich mixtures modelled in another publication [6]. A much larger wax deposits formed due to the flow of the 100% oil stream in Case 10 can be seen Fig. (4), that shows 4mm deposits being formed after merely 22 hours. The irregularities in the results along the profile are caused by the cooler downward bends. For estimating the τ based on the methodology described herein, the pressure drop sensors in three segments were used for Cases 1-9 and the temperature sensor near the outlet section was employed for Case 10, due to the very low flow rates of this scenario. Uncertainties and sf values of 37.5 Pa (high precision ΔP sensor) and 2 and of 0.5°C (Pt100 after installation) and 10 were considered.

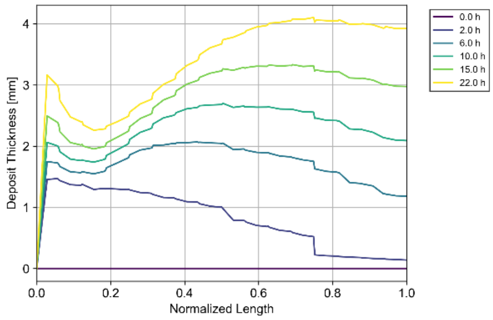

Figure 4. Wax deposition for Case 10.

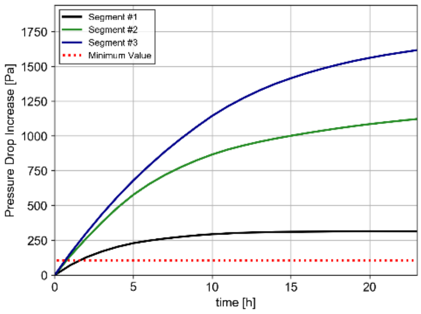

Figure 5. Pressure drop increase due to wax deposition (Case 1).

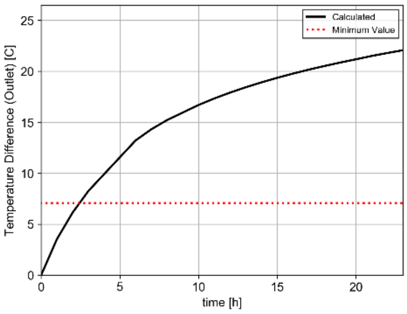

Figure 6. Temperature difference near the outlet section due to wax deposition (Case 10).

The comparison between the time evolution of the wax deposits impact on the pressure drop at the three segments (for Case 1) and on the temperature near the outlet section (for Case 10) can be seen in Figs. (5) and (6), which reveal the methodology for estimating the τ values based on the aforementioned parameters. This methodology shall be compared with experimental data for validation purposes. Returning to the τ results in Tab. 1, it worth seen that the maximum τ value was 25.23 hours, which is a very feasible value for an experiment. Nonetheless, more valuable than the absolute value of τ's, are how they are influenced by pressure, Q_G and LVF. Firstly, the greater the Q_G value, the more sensitive the pressure drop values are to the wax deposited growth, which reduces the τ values. Naturally, the larger the LVF, the greater the fraction of paraffinic components in the mixture and the larger the wax deposition rates. Lastly, the lower the operating pressure, the lower the mixture densities and pressure drops. Which translates in a thicker required wax deposit for the pressure drop sensors to detect it.

Conclusions

This paper discusses a methodology, utilizing simulation tools, for estimating the minimum duration of experiments to investigate wax deposition. This investigation was based on a subsea cooler prototype, under a high-pressure CO_2-rich mixture flow with small waxy oil contents. Based on the simulation results, it could be proposed what is the minimum duration to measure the deposit, based on the temperatures and pressure drop. Future improvements of this methodology mainly include enhancements in the 1D steady-state model as well as to test other wax deposition models, such as the one solely based on heat transfer mechanism [3]. Moreover, the flow and wax deposition predictions shown in the paper shall be validated against the measurements of a future experimental campaign for the prototype, as well as against field data for a full-scale subsea cooler under development.

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