Project 1– Wax Deposition under Two-Phase Flow at Different Flow Patterns

Objectives

The general objectives of this study are to develop the more reliable model for two-phase (oil-gas) flow by integrating the deposition behavior observed from the available experimental data and to elucidate the impact of flow patterns in two-phase oil and water flow on wax deposition mechanism.

Project Description

This project will be conducted in two parallel tracks. It is well known that the flow patterns influence the behavior of wax deposition in multiphase flow. In the past, TUPDP successfully has experimentally studied the wax deposition in slug and stratified flow of Garden Banks oil and natural gas. The experimental data are essential to developing a more reliable mechanistic model for wax deposition in two-phase flow.

- Track 1: A more reliable and comprehensive model for two-phase flow will be developed by integrating the deposition behavior observed from the systematic experimental approach. This will be accomplished by utilizing the data of two-phase flow studies such as Chi (2018), Rittirong (2014), Kilincer (2003), Manabe (2001), and Matzain (1999).
- Track 2: Understanding of two-phase (oil and water) flow wax deposition will enhance our fundamental understanding and improve the ability of the systematic study of more complex cases (multiphase flow of oil-gas-water). The experimental data will be essential to develop a more reliable mechanistic model for wax deposition in multiphase flow. This project will be a continuation of the previous project (Chi, 2018) in TUPDP. The multiphase flow loop facility will be used for oil-water wax deposition in different flow patterns. Experiments will be conducted to investigate the effect of flow patterns, heat transfer on the oil-water wax deposition process. Hydrodynamic tests will be conducted first utilizing the high-pressure sapphire window cell to determine the flow pattern, pressure drop, liquid holdup, and any other required parameters. Once the hydrodynamic conditions for flow patterns are determined, the wax deposition experiments at different heat transfer and shear will be conducted.

Project 2– Mechanistic Study of Turbulent Flow Wax Deposition

Objective

The objective of this study is the microscopic visual investigation of the wax deposition at the fluid-deposition interface under different shear rates. The possible outcomes of this study will enhance our understanding of mechanisms of wax deposition under flowing conditions and serve as a basis for the development of better deposition models or closure relationships.

Project Description

High uncertainties are common in wax deposition models. The inherent problems with available wax deposition models are:

- **Can the models be used as reliable predictive tools for field cases?** - Available models use fitting parameters that were obtained from limited laboratory data set. A model cannot be used as a predictive tool unless those fitting parameter values can be pre-determined in a reasonably accurate manner based on known inputs. The absence of adequate closure relationships in available models prevents the utilization of them as reliable predictive tools. With a substantial degree of empiricisms, the up-scaling of wax deposition models to field cases is difficult due to the diversity of the produced fluids and operating conditions. The models need to have a stronger physical basis to reduce uncertainties.
- **Physical mechanisms by which shear force affect deposition are still unclear** - Various hypotheses, which require satisfactory physical validation, have been proposed. The hypotheses affect the mathematical formulation of the model and all associated closure relationships. Consequently, model formulations tend to be empirical and not mechanistic. Microscopic visualization investigation of wax deposition is aimed to elucidate the physical mechanisms due to shear (low and high) and drive towards reliable closure relationships in the existing and new models.

A step-by-step process from static to laminar and finally to turbulent flow conditions is required given the limited references on experimental setup and procedures. Since the initiation of this project in the fourth quarter of 2013, TUPDP has completed project scoping, the establishment of the experimental setup, procedure, and semi-quantitative analysis technique, and completion of static test experiments. A dynamic visualization setup was built and incorporated into the TUPDP mini loop facility. This setup will be modified with a high-resolution camera and new cell and used for microscopic experiments using model oil (mineral oil – food grade wax mixture). A semi-quantitative analysis will be applied to the visualization results as applicable.

Project 3 – TUWAX Software Maintenance and Development

Objectives

The objectives of this project are to maintain TUWAX software compatibility and functionality and to improve TUWAX software by updating and incorporating additional paraffin deposition models and simulation algorithms

Project Description

TUWAX software is a paraffin deposition simulator developed by Tulsa University Paraffin Deposition Projects (TUPDP). It is capable of simulating single-phase and multiphase mixture paraffin deposition, e.g., average deposit thickness and wax fraction as a function of axial length and time. The software is composed of a graphic user interface written in MS-Excel VBA for parameter input and result visualization, while the main simulation modules are developed with FORTRAN language. WAXPro Steady State model has several modules, subroutines, and functions. The main modules are momentum, heat transfer, pipeline integration, PVT properties, and numerical methods. Continual maintenance is required to ensure the program functionality and run effectively without any bugs. Moreover, further improvements by incorporating additional

paraffin deposition models, simulation algorithms, and experimental results into the program are necessary. The proposed TUWAX software maintenance and development can be summarized as follows:

Project 4 – Experimental Investigation into the Role of Gelation on Wax Deposition to Guide Scale-up and the Design of Wax Inhibitor Treatment Programs

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Objectives

The general objectives of this study are:

- To develop a reliable wax deposition modeling workflow, involving experimental characterizations at lab-scale and modeling approaches, to predict wax deposition at field scale.
- To improve the current practice for wax inhibitor treatment design using the workflow as mentioned above and to achieve reliable quantitative recommendations with the improved testing and/or scale-up methods

Project Description

It has been well understood that wax deposition on the inner wall of oil transportation pipelines is driven by radial molecular diffusion of dissolved wax molecules. As a result, contemporary wax deposition models are largely developed based on mathematical descriptions of molecular diffusion. However, it should be noted that diffusion-based wax deposition models present significant limitations when applied to study the effect of wax inhibitors on wax deposition as the altered rheology of the oil and deposit due to additives is not captured. Because of the same limitation, existing wax deposition models, in general, cannot predict the reduction of wax deposits with increasing shear. To model the effect of shear and wax inhibitors on the wax deposition, the wax deposition model needs to link the shear imposed by the fluid with the rheology and the gelation process in the vicinity of the pipe wall. Preliminary investigations jointly conducted by SWTS and Chevron have shown that combining rheological characterization with wax deposition modeling is promising to enhance wax deposition models for the application of wax inhibitor treatment design. To advance the understanding of the role of gelation on wax deposition and develop more reliable methodologies to predict wax deposition rates under various conditions and with chemical treatments, an experimental investigation into the role of gelation on wax deposition is proposed.

Proposed Program

Experimental:

Step 1: Wax deposition experiments under controlled temperature driving force and wall shear stress (rate) to form the incipient deposit layers for rheological characterizations

- With and without wax inhibitor
- Different geometry

- Microscopic flow cell – the goal is not to quantify deposit mass but use this technique as a visual aid to observe morphological change induced by chemicals.
- Flow loop (with different pipe diameter, start with the 1-in loop)

Step 2: Characterization of the incipient deposit gelation solid fraction under the same controlled shear stress using a rheometer

Simulation:

Explore tweaks in TUWAX to incorporate the effect of the solid fraction of the incipient deposit and predict the change in the wax deposition rate due to the addition of chemicals or varying shear conditions in the experimental programs.

Project 5– Thermal Removal of Wax Deposits

Objective

The general objective of this study is to provide guidelines in terms of temperature target to remove wax deposits by heat tracing the wall and by circulating a warm fluid.

Motivation

Operators are considering more and more single lines with electrical heating to manage wax and hydrates without any facility to deploy operational pigging. One idea to limit power utilization could be to maintain the temperature below the WAT during nominal production and to heat the line periodically to remove the deposit.

With no electrical heating, another remediation method could be to circulate hot fluid in the line. The question for both cases is: what is the minimum temperature to remove the deposit?

Many understand that the WAT of wax deposits is significantly higher than the WAT of the oil. Therefore, it could be foreseen to bring the deposit at a temperature much higher than the WAT of the oil. This is implicitly associated with removal based on a melting process of the deposit.

Within TOTAL, feedback from the field and a few observations in laboratory cells seem to indicate that the deposit removal can be achieved at a temperature even lower than the WAT of the oil. In these cases, the removal may be explained by a "disbondment" of the deposit from the wall.

Project description

It is proposed to form different wax deposits in the loop under single flow conditions and to detect the onset temperature above which a removal process is observed.

A typical series of tests is as follows:

- Wax deposit formation in the loop
  - Record of the evolution of the pressure drop during deposit formation
  - Recover the wax deposit for characterization (wax content, WAT)
- Repeat the wax deposit formation to investigate the deposit removal by wall heating

    - Check the repeatability by comparing the evolution of the pressure drop during formation
    - Increase the wall temperature step by step
        - Detection of the removal process from the evolution of the pressure drop
- Repeat the wax deposit formation to investigate the deposit removal by fluid heating
    - Check the repeatability by comparing the evolution of the pressure drop during formation
    - Increase the fluid temperature step by step
        - Detection of the removal process from the evolution of the pressure drop

Project Deliverables

Project 1 – Wax Deposition Under Two-Phase Flow at Different Flow Patterns

1. Development of a comprehensive two-phase paraffin deposition model and its incorporation in TUWAX software.
2. Paraffin deposition characterization and the effect of heat transfer on wax deposition under oil-water flow.

Project 2 – Mechanistic Study of Turbulent Flow Wax Deposition

The results of the investigation of several proposed hypotheses, as given below, will be provided.

- **Shear effect on crystal morphology** - Crystal aspect ratio is one of the fitting parameters in wax deposition models. Based on flow loop data, it is assumed to be lower at higher flow rate and consequently is responsible for more aging. There are no physical proof and closure relationship for this interpretation to this date. The validation method would be microscopic visualization of static, laminar, and turbulent flow conditions.
- **Shear reduction mechanism** - The two main hypotheses of shear reduction mechanism are shear stripping and shear prevention both resulting in reduction of net wax mass flux into the deposit. Shear stripping assumes that the deposited wax may be removed/ sloughed due to high shear while shear prevention generally assumes that shear effect reduces the incoming wax mass flux from bulk to deposit or hinders deposit growth. Shear stripping can be validated qualitatively through microscope observation at turbulent conditions.
- **Precipitation kinetics in boundary layer** - At high flow rates, the wax concentration in boundary layer is expected to be more super-saturated due to higher equivalent cooling rate. However, direct heat-mass transfer analogy (film mass transfer) is observed to over-predict the super-saturation (and correspondingly wax mass flux). Precipitation kinetics determine the degree of wax super-saturation in boundary layer, which is bounded by film mass transfer and equilibrium model concentration profile. Microscopic observation in boundary layer is planned to qualitatively assess magnitude of precipitation with varying flow rates.
- **Particle entrapment in initial deposition stage** - This hypothesis suggests that precipitated wax crystals might be entrapped during initial stage of deposition. If occurs, this phenomena will lead to enhancement of initial deposition/ aging rate on top of molecular diffusion. Microscopic visualization near the cold wall region is planned as qualitative verification.
- **Crystal deformation due to shear** - This hypothesis suggests that shear may deform the wax deposit crystals which lead to change in thickness and wax content. High magnification visualization on wax deposit crystals is planned to qualitatively verify this hypothesis.

Project 3 – TUWAX Software Maintenance and Development

The expected deliverables of TUWAX software maintenance and development for the current and future projected phases can be summarized as follows:

- Full Integration with TUFFP for momentum transfer
- Develop the Fortran and Excel Beta versions of the steady state and pseudo steady state solution
- Identify and fix all of the bugs that stop the program from functioning. This includes compatibility errors from different Windows, Excel VBA, and FORTRAN versions.
- Modify Excel user interface to make it more user friendly and easier to use. Moreover, improve visualization of the program e.g. pipeline schematic and result plotting.
- Direct use of different format thermodynamic look tables without conversion
- Review and validate numerical algorithm which is existed in the program to ensure the correctness and improve the simulator.
- Extend the prediction of wax deposition to multiphase flow
- Complete manual with examples and tutorials

Project 4 – Experimental Investigation into the Role of Gelation on Wax Deposition to Guide Scale-up and the Design of Wax Inhibitor Treatment Programs

Flow loop wax deposition experiments with and without wax inhibitor:

- Deposit weight data at the end of the experiments
- Incipient deposit samples
- Wax precipitation characterization of the incipient deposit samples by DSC

Rheological characterization:

- Viscosity – temperature relationship under constant shear stress of the incipient wax deposit samples collected from the flow loop experiments

Simulation results:

- Exploratory TUWAX wax deposition modeling results

Project 5 – Thermal removal of wax deposits

- Target temperatures for deposit removal depending on deposit properties in terms of wax content and WAT