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Online estimation of wax deposition thickness in single-phase sub-sea pipelines based on acoustic chemometrics: A feasibility study

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HIGHLIGHTS

- ▶ Estimation of wax deposition thickness in pipelines based on acoustic chemometrics.
- ▶ Partial least squares regression was applied in estimating wax deposition thickness.
- ▶ Validation results for the wax deposition thickness model were satisfactory.
- ▶ Further investigations and subsequent implementation are recommended.

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ABSTRACT

Wax deposition in sub-sea oil producing pipelines is a concern to the oil producing companies. The deposition of wax in pipelines can cause serious economic implications if not monitored and controlled. Several researchers have developed models and investigated the deposition of wax in crude oil pipelines. As of today, there is no *off the shelf* instrument available for reliable online estimation of the wax deposition thickness in sub-sea pipelines. Acoustic chemometrics was applied to investigate the potential for online estimation of wax deposition thickness in sub-sea pipelines. This feasibility study was carried out as a so called *piggy back* on experiments performed at Statoil research centre in Porsgrunn, Norway with real crude oil or waxy gas condensate. The first investigations focused on the repeatability of the acoustic chemometric technique followed by online prediction of the wax deposition thickness in a single-phase oil flow pipeline. A partial least squares regression model was calibrated and validated with a totally independent data set. The calibrated model had a root mean squared error of prediction of 0.28 mm with a final wax deposition thickness of 3.36 mm, a slope of 0.91 and R^2 of 0.83 which were satisfactory results. The effect of varying oil flow rates on the wax deposition thickness was also investigated. The preliminary results showed the need for further investigations based on a robust experimental design and sample pre-processing. The general conclusion that can be drawn from this feasibility study was that the potential of adapting the acoustic chemometric technique for online estimation of the wax deposition thickness exist and must be further investigated.

1. Introduction

There is an increase in demand for petroleum and its allied products due to the rapid increase in the worlds' population even though the worlds' oil production has reached its peak [1]. Several oil producing companies are now developing marginal oil wells and drilling in deeper depths below sea level as a result of the increase in demand coupled with the increase in price of crude oil on the international market. A major concern in the transportation of crude oil from oil reservoirs is flow assurance. Wax deposition in oil pipelines is a flow assurance issue. The deposition in sub-sea oil producing pipelines is one of the major obstacles for operating long sub-sea single-phase or multiphase flow pipes. Transportation of crude oil from the oil reservoir may result in the deposition of wax from the petroleum fluids. Wax precipitation is a result of cooling of the sub-sea pipeline by the ocean which is typically at a temperature of 4 °C whilst the reservoir temperature and pressure is between 70 and 150 °C and >2000 psi respectively [2]. The heat transfer from the crude oil to the ocean is mainly a result of convection and conduction heat transfer. The temperature at which the first wax appears is commonly referred to as wax appearance temperature (WAT).

When wax deposits in oil pipelines, these deposits must be monitored continuously and removed when the deposits have

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the tendency to affect production. There are several methodologies that can be applied in removing the wax deposits including heating, pigging operations, addition of wax inhibitors whilst pipe line insulations can be applied in preventing wax deposition. All these methodologies have their advantages and disadvantages. Pigging is the most widely used operation in removing wax deposits in pipelines due to the advantages that this technique possesses over the others. Faster wax deposition in pipelines results in a more frequent and risky pigging operation [3]. When the wax is allowed to grow for a long period, the effective cross-sectional area of the pipeline is reduced. At higher wax deposition rates the tendency for the pigs to get stuck in the pipe is great. Ageing of wax in the production pipeline is also an important area of research with respect to wax deposition. Several researchers have developed wax ageing models and these models have been reviewed by Aiyejina et al. [4]. In cases where production must be stopped in order to remove the plugged portions of the pipeline due to large wax deposits, the cost involved in replacement and downtime was estimated by Huang et al. as ~$30,000,000 whilst in severe cases the platform could be abandoned at a cost of $100,000,000. Thus wax deposition can cause devastating economic implications to the oil producing company [2].

Wax deposition in pipelines is influenced by several factors including crude oil composition, temperature, flow rate, pressure and thermal history [5]. This flow assurance problem has been a major research topic for some time now. Several researchers have studied and proposed methodologies [6–11] for detecting wax deposition. Aiyejina et al. [4] have reviewed wax formation in oil pipelines. In their critical review, deposition mechanisms including wax deposition models were captured. Hoffmann et al. [12] proposed an online wax thickness build-up monitoring technique in sub-sea oil pipeline based on heat pulse monitoring. The availability of a reliable and accurate online wax deposition thickness instrument/technique will be a major break through to the oil producing companies. This instrument if available will not only reduce the cost of production but also enable the oil producing companies to develop oil wells which contain high wax content. As a result of this development, the worlds' oil production would be increased to meet the demand of the ever growing population.

Acoustic chemometrics is a general process monitoring technique which has been adapted in several industries as an alternative process monitoring solution. Literature on the adaptation of the developed acoustic chemometric principle as an alternative process monitoring solution in the oil industry is limited since its inception. Arvoh et al. [13,14], adapted the acoustic chemometric technique for online estimation of both the reject gas and liquid flow rates in a compact flotation unit for produced water treatment. From that study, it was clear that the potential application of this technique in the oil industry is bright. Acoustic chemometrics was the process monitoring solution considered in this feasibility study for online estimation of the wax deposition thickness in a single-phase sub-sea oil flow pipeline.

The feasibility study is a *piggy back* on the single-phase experimental investigations conducted and reported by Hoffmann and Amundsen [15]. The main objective for the experiments conducted in Hoffmann and Amundsen was to obtain experimental data to validate the basic assumptions of a model since field data from production pipelines are difficult to obtain. The experiments were conducted in a 50.8 mm (2 in.) flow loop experimental facility at Statoil research centre in Porsgrunn, Norway. In these investigations real waxy gas condensate from the North Sea flows through a test section surrounded by water annulus to simulate sub-sea conditions. In this feasibility study both principal component analyses (PCA) and partial least square regression (PLS-R) were applied to signals from the acoustic sensor to investigate the potential application of this technique for online estimation of the wax deposition thickness in a single-phase sub-sea oil pipeline. The reference measurements adopted in this study were based on pressure drop measurements and measured final wax deposition thickness by weight which was reported in [15]. The calibrated PLS-R model was validated with a fully independent data set. Evaluation of the model was based on the root mean squared error of prediction (RMSEP), slope, offset, correlation coefficient, explained residual validation variance plot and the score plots. The results for online estimation of the wax deposition thickness in this experimental study is presented and discussed. The results showed that the potential for adapting the acoustic chemometric technique for online estimation of wax deposition thickness in sub-sea pipelines exist and hence further research into the adaptation of this technique is currently ongoing.

2. Materials and methods

Acoustic chemometrics was the technique of choice adopted for online estimation of wax deposition thickness in single-phase pipeline. The *piggy back* nature of these investigations was an advantage for proposing this technique since the measurements and data logging mechanism requires little/no supervision. Besides that, acoustic chemometrics also possesses several advantages over traditional monitoring principles which include:

- Online operation.
- Real time predictions.
- Easy clamp on sensors.
- Non intrusive/invasive measurements.
- Time saving with the use of empirical modelling.

Whilst this technique possesses several advantages, the main disadvantage associated with this technique as with all other chemometric methods is the need for reference measurements. Besides that, this technique is considered a "point measurement" since in wax deposition the changes in wax deposition thickness in the pipeline occurs over several kilometres in the pipeline.

2.1. Flow loop

The wax deposition experimental test facility at Statoil research centre in Porsgrunn, Norway consist of a flow loop where real crude oil or gas condensate is circulated from a tank to the test section (Fig. 1). For detailed description of the experimental facility interested readers are referred to Hoffmann and Amundsen [15]. In this feasibility study only a brief description of the experimental facility is presented. The 5.5 m long test section is surrounded by an annulus through which the counter current water flows. Both the oil and water temperatures in the experimental facility can be adjusted separately between 5 °C and 70 °C, implying that different temperature conditions can be investigated. The total volume of crude oil or gas condensate in the tank was 2000 L, thus wax depletion during the experimental period was not an issue. The experimental rig was operated with crude oil and gas condensate at atmospheric pressure. The rig was equipped with a pump capable of delivering crude oil or gas condensate with volumetric flow rates in the range of 3–30 m^3/h. A coriolis flow metre was used to monitor the volumetric flow rate (Table 1). Stainless steel pipe with 50.8 mm (2 in.) internal diametre was used in these experiments.

2.2. Experimental

Waxy condensate from a North Sea receiving terminal was used in all single-phase experiments investigated in this study. The