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Effects of cooling regime on the formation of voids in statically cooled waxy crude oil

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ABSTRACT

Waxy crude oil solidifies when exposed to certain range of low seabed temperature. In this condition, predicting an accurate restart pressure in the pipeline has remained to be a challenge. Recent researches highlighted that the presence of gas voids in the gel has an impact on the gelled crude oil morphology and consequently on the restarting pressure. The gelling due to cooling of the oil is complex and not well understood. This study is aimed at analyzing the effects of cooling regimes on the formation of gas voids along and across the pipeline using a 3 T Magnetic Resonance Imaging (3 T-MRI) system. A flow loop rig simulating offshore oil transportation was designed and developed to produce the gel. It was found that voids were formed within gelled crude oil by 11.3% in volume. The results from the cooling regime under constant start temperature showed that the widest cooling regime resulted in a maximum voids volume in all regions in the pipe. However, reducing the cooling regime did not guarantee a decrease in volume of voids, for which lower cooling regimes occasionally resulted in a higher percentage of voids volume. For the cooling regimes under constant end temperature, in general, an increase in cooling regime resulted in a higher percentage of voids volume in the gel at lower end temperature. On the contrary, the intra-gel voids formation at higher end temperature was found to be different and a higher cooling regime did not result in a higher voids volume near pipe wall. Indeed, a higher cooling regime formed a higher percentage of voids volume around pipe core.

Introduction

Once a waxy crude oil leaves a reservoir and flows through a subsea pipeline resting on the cold ocean floor, the temperature of the waxy crude oil drops below the wax appearance temperature due to temperature gradients (Ijeomah et al., 2008 and Oh et al., 2009). Lionetto et al. (2007) reported that wax contents within 1–6% would lead to the gelation of waxy crude oil resulting in phase transition and gel formation. Visintin et al. (2005) showed the crystalline nature of waxes in gel using NMR and X-ray diffraction, primarily because of the isoparaffin content in the waxes beside n-paraffin in prime amount. Sanjay et al. (1995) stated that n-paraffin (linear chain) is responsible for the formation of gel following sufficient cooling at the production fields. Aiyejina et al. (2011) pointed out that the deposition of waxes in pipelines carrying waxy crude oil was a complex phenomenon which depends on the composition, pressure and temperature, heat and mass transfer, and phase interaction, including solid–solid and solid–liquid interaction.

Waxy crude oil changes from a low viscosity Newtonian to a high viscosity shear thinning and thixotropic product during cooling due to the precipitation of paraffin particles (Vinay et al., 2005). The restarting process for a gel with high strength and complex structure requires a high pressure which makes it difficult and sometimes impossible (Wheeler et al., 1989). Field cases and laboratory tests have shown that the conservative equation for predicting restart pressure led to an overestimation of pressure and pipeline dimensions. Designs based on such estimation result in additional pipeline insulation and pumping station requirements which would increase capital investment (Margarone et al., 2010). Most models developed to predict the restart pressure were based on numerical method approach. The non-Newtonian properties of gelled crude oil were also not considered in the task of predicting an accurate restart pressure (Aiyejina et al., 2011). Waches et al. (2009) presented a new analytical relation predicting the restart pressure. Their model showed that the restart process of a thixotropic and viscoplastic fluid, with a compressibility combined, can be accomplished with a lower pressure drop compared with the pressure drop estimated using the conservative equation of $\Delta P = 4\tau_y D / L$. Ajienka and Ikoku (1995) also developed a model that resulted in a lower restart pressure than the values from the conservative method.

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Luthi (2013) measured restart pressure to understand the complex process of pipeline start-up. They noted that breaking up of a gel structure depended on thermal shrinkage, thermal effects, thixotropy, compressibility, and aging which made the yielding process to be time dependent variable. The authors reported the unnecessary costs spent on the pipeline systems if the factors affecting the restart pressure were not considered. They also pointed out many factors that were not included in the conservative equation. The restart pressure obtained was much lower than the values from the theoretical equation, evidencing the over predicted pump and pipeline systems.

The next major challenge for oil industry is the prediction of wax deposition and restart pressure in multiphase flow (Lee, 2008). Jemmett et al. (2012) evidenced the multiphase behavior of waxy crude oil gel. The multiphase behavior usually appeared when the sample temperature was below the pour point, with the solid gel, gas voids formed in a gel and some liquid oil entrapped in the wax crystals, forming three phases in the fluid. Despite great interest in multiphase wax gelation, practically little work is available to demonstrate the exact effects of the presence of gas on the rheology of the multiphase fluid. The presence of gas in a flowing fluid apparently reduces the pour point of composite fluid mainly because the free gas distributed in the crude oil acquires additional pressure energy to deform the waxy gel flow (Rai et al., 1996). Ramirez-Jaramillo et al. (2010) performed a study on the effects of deposition geometry on flow parameters considering a multiphase fluid flow through production lines. They observed that the existence of gases in waxy crude oil affected the nature of deposition and flow parameters, mainly pressure drop.

One of the important fluid characteristics that was not considered during the calculation of the restart pressure is the compressibility of the gelled crude oil. The formation of gas voids as a result of thermal shrinkage, for instance, makes waxy crude oil to be compressible fluid (Garcia-Salas et al., 2005). Liu et al. (2014) conducted experiment on the compressibility of waxy crude oil under both liquid and gel state. They observed that the compressibility of liquid crude oil at Newtonian region was lower than that of the gelled crude oil. The compressibility was also observed to decrease when the gel structure was broken down with a higher pressure and gas voids within started disappearing following the yielding of the gel. Frigaard et al. (2007) highlighted the principal advantages earned when the compressibility effects on restart pressure was considered, which gave a lower pressure drop at the inlet of the pipe and a reduced time to displace the gel. Zhang et al. (2014) outlined that the compressibility of a gel allowed fresh Newtonian liquid crude oil to push and replace a fraction of a plugged gel, and ultimately produced higher shear stresses in the gel, which led to strong pressure drop at the upstream region of the pipe.

Prevention of wax deposits using different techniques was found to only retard the precipitation and deposition of waxes in waxy crude oil. Fleyfel et al. (2004) evidenced that the use of insulation coating on a pipe could not prevent wax precipitation during both shut down and steady state flowing conditions. Smith and Ramsden (1978) also observed the rapid change in the cooling rate of waxy crude oil inside an insulated pipe under shutdown condition, indicating that the prevention of wax deposition with an aid of insulation is almost impossible. Waxy crude oil under cooling condition experiences thermal shrinkage due to a heat loss as a result of temperature gradient between the waxy crude oil and ambient temperature at seabed. Thermal shrinkage mainly causes waxy crude oil to shrink, and voids would then be formed in a gel, which would make the actual restart pressure in a pump to be much lower than what was predicted from the theoretical equations. Magda et al. (2013) conducted experiments in a laboratory flow loop in view of restart pressure. They produced gel under two different conditions: atmospheric pressure and under constant upstream pressure to minimize the formation of gas voids in a gel. It was reported that the gel formed under the latter condition was difficult to be restarted, indicating the reduced restart pressure as a result of the voids formed.

Borghi et al. (2003) reviewed the level of waxy crude oil restart for an operation performed under challenging environment in deep water. They evidenced an over-predicted restart pressure in significant value following series of laboratory experiments. They stated that the over-predicted restart pressure can be accurately optimized by considering compressibility and solid-like fracture in the gel. Ahmadpour et al. (2014) discussed theoretically the weakly compressible nature of gelled waxy crude oil due to thermal shrinkage. They discussed that the voids in a gel nullify the assumption of incompressible of the gel in the theoretical equation. Vieira et al. (2009) also reported that presence of gases in waxy crude oil would reduce wax appearance temperature of the sample, acting as a solvent for the paraffin. The voids formed in a gel, particularly around pipe wall, would reduce the stress between the wall and gel and consequently reduce the restart pressure at significant level (Chala et al., 2014). However, there have been no appropriate experimental works reported to precisely locate and relate gas voids formed with the cooling regimes of the waxy crude oil gel. The objective of the present study was therefore to investigate the effects of cooling regimes on the formation of voids in the gel using the 3 T-MRI system.

Experimental setup and techniques

Experimental flow loop rig

Fig. 1 shows a schematic of the experimental rig. The rig encompasses different main components, namely, a crude oil tank equipped with heater and stirrer motor, a gear pump, a centrifugal pump, and a test section pipe immersed inside chilled water. A micro-motion transmitter was installed between the gear pump and the test section to measure volume and mass flow rate of waxy crude oil, including density of the sample. The test section pipe (acrylic pipe) was made from a transparent non-metallic material for the MRI scanning purpose and to visualize the cooling process and gel formation. It was a detachable pipe with a uniform diameter of 30 mm and length of 1.2 m. The pipe was immersed in a water bath cooled using a chiller to simulate a subsea pipeline carrying a gelled crude oil. Constant flow of water was maintained to ensure homogeneous cooling of the waxy crude oil in cold reservoir.

A computer controlled data acquisition system was used to record the properties of waxy crude oil in the pipelines during the cooling process. The measured properties included the temperature of the chilled water, the temperatures of the waxy crude oil both at the inlet and outlet of the test section pipe and the temperature of the waxy crude oil while undergoing cooling process in the acrylic pipe. Pressures at the inlet and outlet of the test section pipe were also measured using digital pressure transducers.

Characteristics of the waxy crude oil

Waxy crude oil, which was obtained from an undisclosed field in the South China Sea, was utilized for analyzing voids formation within the gelled crude oil. The wax appearance and pour point temperatures and other properties of the fluid are shown in Table 1. The sample used has a density of 850 kg/m^3 and viscosity of 0.002 Pa s in the Newtonian region, within which the viscosity remains independent with its temperature. Waxy crude oil exhibits time and temperature dependent rheological properties in the non-Newtonian region.

Experimental techniques

In the present study, cooling regime refers to temperature difference between the start and end temperatures of the sample. The