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Gas void formation in statically cooled waxy crude oil

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ABSTRACT

If a gel is formed when the flow of waxy crude oil within a pipeline is stopped for a period of time, the required restart pressure may be high and the line is costly to operate. The conventional method of predicting the restart pressure for gelled crude oil assumes a constant yield stress across and along the pipe section; this often leads to excessive over sizing of pump and piping system. Many researches highlighted that the presence of gas voids upon cooling of waxy crude may have an impact on the yield stress of gelled crude. This paper describes the use of Magnetic Resonance Imaging (MRI) to investigate the formation behaviour of gas voids within a gelled crude oil sample from a field in the South China Sea. Scanning of gelled crude at selected temperatures was performed following cooling in the circular pipe section within an experimental flow loop rig. Gas voids within the range of 7–12% were observed in the gelled samples resulted from different cooling temperatures and cooling rates. The cooling temperature and cooling rates were observed to influence significantly the location and volume of gas voids formed within the gelled samples. Higher cooling rates resulted in higher volume of gas voids close to pipe wall while lower cooling rates resulted in more gas voids located around core of the pipe.

1. Introduction

In the event when transportation of waxy crude oil in a pipeline is stopped due to a planned maintenance or in an emergency situation, the temperature and solubility of the oil at seabed would decrease and at below wax appearance temperature, wax molecules would precipitate out of the liquid phase in a static condition [1–3]. Under these circumstances, precipitation of waxes subsequently leads to the formation of waxy-oil gel that could eventually encompass the whole cross-section of the pipeline if no intervention steps were taken [4–7]. In offshore oil production, the need to displace and subsequently restart a waxy crude oil flow within the pipeline has always been a challenge due to the high yield strength of the crude. Generally, the management of waxy crude oil and gel involves high costs.

Several mitigating and remediation strategies can be adopted to avoid the problem of restarting. As the wax gelation may occur simultaneously with wax precipitation and deposition [8], the main goal is to maintain the pipeline temperature to be above the wax appearance temperature and the pour point temperature as well to minimize accumulation of wax deposits. Thermal mitigation strategy includes heating and insulation. Heat tracing is especially beneficial during shut-in but requires additional power at the topside facility to supply the electrical heating. It is also more challenging for long tie-backs. The more practical approach would be through pipe insulation such as coatings, pipe-in-pipe design or by burying the pipelines. If the tie-back distance is too long, the insulation method alone is not sufficient to maintain the temperature and hence, needs to be coupled with other strategies such as pigging and chemical inhibition [9]. However, these mechanical and chemical mitigation strategies are not applicable during shut-in. If the temperature within the pipeline falls below the pour point temperature and the accumulation of wax is present and not mitigated, it would then lead to severe flow restrictions and eventually a plugged pipeline. To restart the flow, it is critical for the waxy crude oil gel to be displaced by breaking down its rigid structure. The common strategy is to dislodge the gelled oil by pumping another fluid (typically water or light oil) into the pipeline at high pressure [10]. Thus, the knowledge on gelled waxy crude oil properties and behaviour is critical for successful remediation and restarting [11].

Waxy crude oil behaves as a Newtonian fluid when the temperature of the crude oil is higher than the Wax Appearance

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Temperature (WAT), below which non-Newtonian fluid characteristics slowly emerge. Apart from being shear dependent, waxy crude oils are also considered to be a thixotropic material, of which the rheological properties (viscosity and yield stress) depend on the mechanical and thermal history [12,13]. These properties are highly affected by shear to which the fluid is subjected to in addition to the way it is cooled down [14]. Amongst numerous researches on structure of waxy crude oil, Cazaux et al. [15] investigated a gel structure using an X-ray diffraction (XRD) technique, a small angle X-ray scattering (SAXS) technique, a cross-polarized microscope (CPM), and a controlled stress rheometer (CSR). They reported that the key parameters defining the structure of wax-oil gel would be the crystal shape and the number density of wax crystals, of which both would depend on the surrounding temperature and cooling rate of the crude oil. The size and shape of wax crystal in crude oil also depends on the shear rate [10].

Conservative relation adopted in the industry to predict a restart pressure is:

$$\Delta P = 4\tau_y L/D \tag{1}$$

where τ_y is the yield stress needed to break the gel, L is the pipe length and D is the pipe diameter [15]. It comes from a simplified concept that the force required to displace a gel ($\Delta P^* \pi D^2/4$) must be equal to the shear resistance along the wall ($\pi D L \tau_y$) of the conduit. This approach assumes that the yield stress (τ_y) is constant across the pipe section and along the total length of the pipeline and that the fluid is incompressible. Margarone et al. [16] developed a one dimensional model supported by experimental validation of gelled waxy oil restart. The model developed underestimated the maximum pressure at the inlet section of the pipe with an error of approximately 20%. It was demonstrated that a superior pump horsepower would be required to restart a flow of waxy crude behaving as an incompressible high viscous fluid. In practice, this will subsequently result in high capital expenditure (billion dollar scale) of pipeline facilities [11].

Despite the extensive use of incompressible fluid assumption leading to a constant yield stress in the restart pressure calculation, waxy-oil gel formations in pipelines were reported to be inhomogeneous due to thermal and shear history in the axial and radial locations inside the pipelines, and thus invalidating the constant yield stress assumption [5]. Henault et al. [17] observed thermal shrinkage after conducting X-ray scanning on several cross sections of a tube and postulated that it would highly influence the mechanical properties of the gelled crude oil. Decrease in the volume of waxy-oil gel during cooling was observed, resulting in local voids in the gel. The non-uniform gel formation in field pipelines could significantly reduce the pressure required to break the waxy-oil gel [4]. This was supported by the work of Wachs et al. [18] using a 1.5D numerical model, in which they demonstrated that flow of waxy crude oil could be restarted with a pumping pressure well below the value predicted by the conservative relation expressed in Eq. (1).

Lee et al. [19] stated that compressibility of the wax-oil gel may contribute to the inconsistencies between the static yield strength measured from the controlled stress rheometer and the model pipeline tests documented in the literature. The compressibility behaviour of waxy crude oil is believed to lead to a significant reduction in pumping pressure at the upstream region of the pipe. Phillips et al. [20] developed a numerical model for the shrinkage study, which was validated by experimental observations. They highlighted the effects of cooling on voids induced by thermal shrinkage within a gelled crude, for which the fluid volume shrinkage could induce axially-directed, shear inducing pipe flow. The rate of shrinkage was found to be directly proportional to the pipeline length to diameter ratio (L/D) implying that increasing L/D may reduce the restart pressure requirements. Direct proportion of rate of shrinkage to the cooling rate was also observed in their work. In another report, Phillips et al. [21] observed that the thermal shrinkage process resulted in cohesive failure of the gelled crude and the formation of voids at locations of low pressure.

At temperatures lower than the wax appearance temperature the crude oil behaves like a non-Newtonian fluid. The crude oil flow behaviour is largely determined by the structure and quality of wax crystals deposited from the solution which will subsequently lead to complete gelation of the crude oil if the temperature is significantly reduced [22]. A Magnetic Resonance Imaging (MRI) scanner may be an imperative tool for imaging and to indicate the extent of the waxy gel crude structure formed in the pipelines. The thermal shrinkage process the crude oil experienced is critical as it will subsequently affect the displacement of the gelled oil in a pipeline during restart process. Therefore, the objective of this work was to observe and quantify gas voids within gelled crude oil as a result of the shrinkage during cooling using the MRI techniques. With the use of MRI, the amount of voids at different points along the pipeline could be addressed in contrast to the other techniques addressed earlier. Consequently, the problem of restarting of flow of waxy crude oil in the pipeline could be addressed in a more rational manner by understanding the nature of voids within the gel.

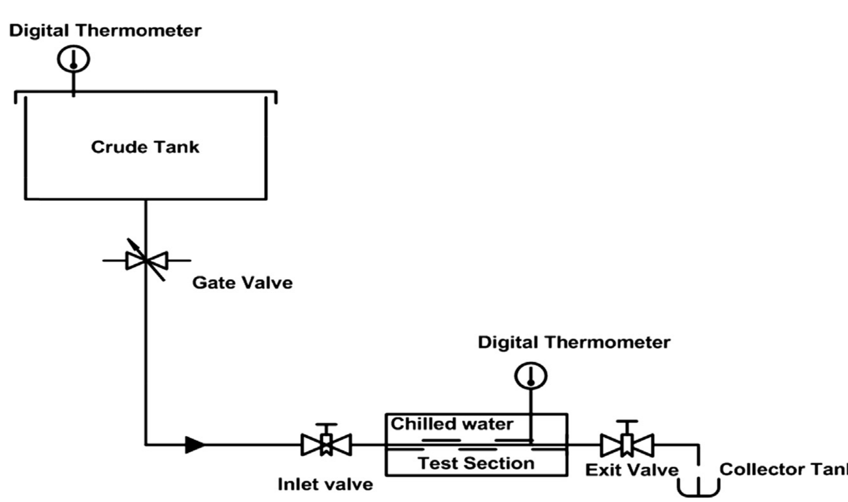

Fig. 1. Schematic diagram of flow loop rig.