

# **The Effect of Gas Injection Duration on the Restart Pressure of Waxy Crude Oil Pipeline**

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## **Abstract**

Waxy crude oil deposition in production pipelines often causes flow assurance issues in production operation. The issue further deteriorates during restarting of the waxy crude oil pipeline after an emergency shut down or planned maintenance. This is due to the obstruction caused by the solid wax in the pipeline, which requires additional pressure to disintegrate the solid wax before achieving a steady flow. The conventional equation used to measure the minimum pressure required for pipeline restart is overestimated, since thermal shrinkage, gas voids formation, and compressibility are neglected. The present study describes the effect of water bath temperature on the cooling time of the waxy crude oil and the effect of gas injection duration on the restart pressure of the waxy crude oil pipeline. The experiment was carried out using a waxy crude oil flow loop rig. It was observed that as the water bath temperature decreases, the cooling time increases, and the cooling rate decreases. When different gas injection durations were injected, a longer duration yields to lower pipeline restart pressure. Longer gas injection duration implies more volume of gas; hence compressibility is increased, which provides more space for the movement of the gelled waxy crude oil and its disintegration within the pipeline during the restart process. Hence, the restart pressure of the pipeline can be greatly reduced. At water bath temperature of 20°C, the highest restart pressure reduction, 40.48% is achieved, whereas at water bath temperature of 32°C, the highest reduction in the restart pressure attained is 33.52%.

## **Keywords**

Waxy crude oil, restart pressure, production pipeline, compressibility, nitrogen gas.

## **1. Introduction**

Crude oil is an unrefined petroleum product with complex mixture of hydrocarbons which is comprised of components such as paraffins, asphaltenes, resins and aromatics. Substances that cause critical flow assurance problems are mostly paraffin wax and asphaltenes which experience thermodynamic instability (Alade, Hassan, Mahmoud, Al-Shehri, & Al-Majed, 2020). It is reported that as high as 50% of paraffin waxes could exist in waxy crude oil (Ajienka & Ikoku, 1991). Essentially, paraffin wax consists of normal paraffin content of approximately 80 to 90%, while the rest is comprised of branched paraffins (iso-paraffins) and cycloparaffins as mentioned by Rehan et al. (Rehan, Nizami, Taylan, Al-Sasi, & Demirbas, 2016). In transporting multiphase hydrocarbons from reservoirs to production surface facilities, the occurrence of waxy crude oil in offshore pipelines is known to be a challenge to the upstream oil and gas operators. It not only reduces the available area to flow but also contributes to production operation delay and requires higher pump capacity to break the wax that clogged the pipelines. It is reported that costly remediation measures were incurred due to the multiple formations of hydrate and wax blockage in the North Sea (Staffa field), which led to an abandonment of the

subsea flowline (Makogon, 2019). Additionally, some Malaysian fields such as Penara, Angsi and Dulang which are located roughly in a water depth of 60m to 70m (Abd Karim, Dahlan, Nordin, & Noor, 2006; Agil, Mohd Saaid, Ibrahim, & Harun, 2008; Kechut, Nadeson, Ahmad, & Raja, 2001), experience wax deposition issues during transportation, in relation to the characteristics of these crude oils, the seabed and surface temperatures and their production histories (Hosseinipour, Japper-Jaafar, & Yusup, 2016).

### 1.1 Objectives

This research aims to investigate the effect of water bath temperature on cooling time of the waxy crude oil in a pipeline. Further to that, the study also includes the effect of gas injection duration on the restart pressure of the waxy crude oil pipeline.

## 2. Literature Review

Due to the rising need for energy, production of crude oil has greatly expanded in both low temperature offshore environments and deep sea regions (Theyab & Yahya, 2018). The oil industry has drilled subsea oil wells up to 160 miles from the shore thanks to deep sea exploration and production technologies that have made deep water drilling commercially viable. The expended transmission line on the low temperature ocean floor may cause wax problems to intensify if oil wells are drilled farther offshore (H. Lee, 2008; Nguyen, 2004). Initially, wax molecules is flowable and appears as liquid phase in crude oil under Newtonian fluid region in a condition where the fluid's viscosity is independent of temperature (Girma T. Chala, Sulaiman, & Japper-Jaafar, 2018). However, as the crude oil flows from the wellbore to the surface, it experiences heat exchange between the crude oil within the pipeline and the surrounding sea water which will decrease the waxy crude oil temperature, eventually increasing the viscosity of the waxy crude oil (Settouti, Ruer, Muguerra, & Spudic, 2020; Yao, Zhang, Zheng, Xing, & Hu, 2022). When this occurs, it creates a resistance to flow to the crude oil. Furthermore, wax molecules begin to crystallize in the long-distance pipelines which encounter temperature reduction on its pipe wall (Alnaimat & Ziauddin, 2020). The transition of crude oil behaviour as Newtonian fluid to non-Newtonian fluid can be observed when its temperature reduced to below wax appearance temperature (WAT) value, where viscosity and viscoelasticity are influenced by shear thinning process. WAT is referred to the temperature at which the first wax crystals begin to form (Aguiar, Nerris, & Mahmoudkhani, 2020). Figure 1 shows a cross-sectional view of a plugged pipeline.

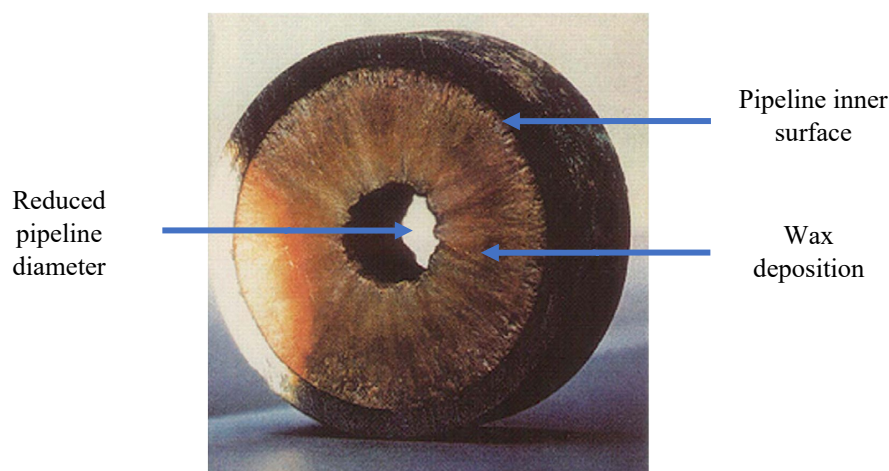


Figure 1. Cross-sectional view of a plugged pipeline (Venkatesan et al., 2005)

Due to the obstruction within the pipeline caused by wax deposition, it is reported that the restarting of gelled crude oil may not be possible sometime, which interferes the smooth crude oil transportation and incurs extra cost to the oil companies (Sulaiman, Chala, & Zainur, 2019). In 1969, the expense of preventing wax build up in U.S domestic production was \$4.5 to \$5 million per year (Theyab & Yahya, 2018). The problem of the start-up of a gelled-crude-oil pipeline has attracted researchers' attention for a long time (Barry, 1971; Davenport & Somper, 1971; Ford, Ells, & Russell, 1965; Liu et al., 2015; Verschuur, Hartog, & Verheul, 1971), which specifically focused on thixotropic properties, viscoelastic behaviour, and yielding behaviour of gelled crude oil (Chang, Boger, & Nguyen, 1998; de Souza Mendes Paulo, 2012; Rønningsen, 1992; Sestak, Charles, Cawkwell, & Houska, 1987). In restarting the production pipeline after a shutdown period, a certain degree of pressure is necessary to initiate flow, to displace the waxy crude oil that has coagulated due to temperature drop below its Pour Point Temperature (PPT). This leads to the demand of larger pumps to disintegrate the wax deposition and

maintain the steady production (Japper-Jaafar, Bhaskoro, Sean, Sariman, & Nugroho, 2015; Vinay, Wachs, & Frigaard, 2009). Typically, the equation used to design the necessary pressure to restart the flow involves a simplistic force balance between the yield stress and the boundary conditions (Ajienska & Ikoku, 1995; Borghi, Corraera, Merlini, & Carniani, 2003; Chang et al., 1998; El-Gendy et al., 2012; Perkins & Turner, 1971; Vinay et al., 2009), which is given by

$$\Delta P_{min} = \frac{4\tau_w L}{D}$$

where,  $\Delta P_{min}$  is minimum required pressure,  $\tau_w$  is shear stress, L is length of pipe, and D is diameter of pipe. Since the equation assumes constant yield stress across and along the pipeline, this results in an overestimation of the pump and piping system. Furthermore, when estimating the pressure needed to restart the coagulated pipelines, the waxy crude oil was believed to be a single phase incompressible fluid (Luthi, 2013). During the quiescent period, waxy crude oil experiences thermal shrinkage as a result of temperature gradient between the crude oil and the surrounding temperature at seabed (Girma T. Chala et al., 2018). In addition, thermal shrinkage is the major factor that cause waxy crude oil to shrink, and gas 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 forecasted from the conventional equation (Girma T. Chala, Sulaiman, Japper-Jaafar, & Abdullah, 2015). However, there are limited studies reported on the effect of gas injection duration on the restart pressure of the waxy crude oil pipeline.

### 3. Methods

#### 3.1 Materials and Equipment

The waxy crude oil samples used in this research are supplied by PETRONAS Carigali Sdn. Bhd. (PCSB) from an undisclosed field. The physical and chemical properties of the crude oil is displayed in Table 1. Density is calculated from the Coriolis flow meter, dynamic viscosity is determined through viscometer, while specific gravity is calculated. The WAT is determined through the ASTM D3117 while Pour Point Temperature (PPT) is obtained through ASTM D97. The experiment rig for waxy crude oil flow loop is as shown in Figure 2.

Table 1. Waxy Crude Oil Sample Properties

Properties	Values
Density	850 kg/m <sup>3</sup>
Dynamic Viscosity	0.002 Pa.s
Specific Gravity	0.85
Wax Appearance Temperature (WAT)	38.5°C
Pour Point Temperature (PPT)	36°C



Figure 2. Experiment rig for waxy crude oil flow loop

### **3.2 Description of Experimental Procedure using Experiment Rig for Waxy Crude Oil Flow Loop**

The experiment procedure is employed from Sulaiman et al. (Sulaiman, Biga, & Chala, 2017) work. The flow loop rig comprises of a test section pipeline made by stainless steel material. The test section which is submerged in a water bath have a diameter of 0.05m and length of 1.2m. The heater of the crude oil storage tank and trace heater which is rolled along the pipelines (except the test section) are switched on concurrently, at a temperature above the WAT. After about five minutes, the electric stirrer motor which is mounted above the crude oil storage tank is switched on to ensure a homogeneous heat distribution within the tank. Then, after about 10 minutes, a gear pump is switched on to build a sufficient pressure to break the gelled crude oil in the test section pipe, eventually initiating flow from the crude oil storage tank to the test section pipe and return to the tank. During the flow of a crude oil in the test section pipeline, water circulation pump is switched on to ensure that the temperature of the water bath to be above the WAT. A chiller system is switched on to reduce the temperature of the water bath to 20°C and 32°C. The water bath temperature is chosen based on the environmental date of seawater temperatures provided by PCSB, where the maximum and minimum temperature is 32°C and 20°C, respectively. When steady crude oil flow is achieved, and thermal histories are removed, nitrogen gas is injected into the inlet section of the pipeline while the crude oil flows at a minimal flow rate before the gear pump is switched off. The flow loop is kept at rest for 45 minutes to allow static cooling of crude oil in the pipelines. After 45 minutes, the flow start-up is achieved by operating the gear pump which allow the pressure to develop at the inlet of the test section pipe until it is sufficient to break the gelled waxy crude oil. All experimental readings were collected by a data logger connected to a computer.

## **4. Results And Discussion**

### **4.1 Effect of Water Bath Temperature on Cooling Time**

Table 2 shows the effect of cooling time of water bath at different temperature, i.e., 20°C, 23°C, 26°C, 29°C and 32°C. The starting water bath temperature (WBT) before cooling takes place is 35°C. The longest cooling time, 3175s is found when WBT is set to cool to 20°C, while the shortest cooling time, 604s is found at the highest WBT, 32°C. The trend shows that the cooling time is inversely proportional with the WBT, however, directly proportional with the cooling rate. As the WBT reduces below the WAT, the thermal gradient yields in the wax deposit formation in the pipeline. The deposit layer generates an additional thermal resistance, which reduces the heat transfer rate between the waxy crude oil and the surrounding WBT, as highlighted by Sina et al. (Ehsani, Haj-Shafiei, & Mehrotra, 2019). This is also consistent with the findings from Chala et al. (Girma T Chala, Shaharin, Azuraian, & Wan Ahmad Kamil, 2016) which found that the heat transfer decreases with reduction in waxy crude oil temperatures, at which wax starts to nucleate. The heat transfer decrement is due to the formation of wax crystals with presence of some liquid crude oil entrapped within.

Table 2. Time for cooling and cooling rate at different water bath temperatures

Start Temperature, $T_1$ (°C)	Water Bath Temperature, $T_2$ (°C)	Cooling Time (s)	Cooling Rate (°C/min)
35	20	3175	0.2835
35	23	2536	0.2839
35	26	1856	0.2909
35	29	1215	0.2963
35	32	604	0.2980

### **4.2 Effect of Gas Injection Duration on Restart Pressure**

Table 3 shows the restart pressure of the waxy crude oil pipeline for WBT 20°C and WBT 32°C at different gas injection duration. The highest restart pressures, 2.584 bar and 2.199 bar were attained when no gas is injected, for WBT 20°C and WBT 32°C, respectively. When the gas is injected for a period of 60s till 75s with an increment of 5s each, it is found that WBT show reductions in the restart pressures. The gas injection duration is observed to be inversely proportional with the restart pressure, where, as the gas injection duration increases, the restart pressure decreases. For WBT 20°C, the lowest restart pressure, 1.538 bar is found when the gas is injected for 75s, where it achieved a reduction by 40.48%, compared with the condition of no gas injection. Similarly, the lowest restart pressure for WBT 32°C, which is 1.462 bar is also found when the gas is injected for 75s, with a reduction by 33.52%. The overall trend, as illustrated in Table 3 shows that as the WBT decreases, the restart pressures are found to be increasing. This is due to the wax shear stress is greater at lower

temperatures. As suggested by Mendes et al. (Mendes, Vinay, & Coussot, 2017), during the start-up of the pipeline, the shear stress imposed on the gelled waxy crude oil builds up when inlet pressure from the pump is increased, eventually becoming locally higher compared to the yield stress. Consequently, the flow is initiated as the imposed shear stress exceeds the oil yield stress when a continuous path is created between the entrance of the test section pipe and its exit.

Table 3. Restart pressure at different gas injection duration for WBT 20°C and WBT 32°C

Duration for Gas Injection (s)	Restart Pressure at WBT 20°C (bar)	Restart Pressure at WBT 32°C (bar)
0	2.584	2.199
60	2.159	1.975
65	2.063	1.668
70	1.836	1.544
75	1.538	1.462

Figure 3 and Figure 4 display the propagation of restart pressures of waxy crude oil pipeline versus the restart time at WBT 20°C and WBT 32°C, respectively. The highest restart pressures, 2.584 bar and 2.199 bar are obtained when no gas is injected into the pipeline at WBT 20°C and WBT 32°C, respectively. The restart time for WBT 20°C is between 10s to 19s, whereas the restart time for WBT 32°C is slightly shorter, between 6s to 13s. In Figure 3, the pressure propagation is observed to be quite unsteady when no gas is injected, and when it is injected at 70s and 75s, due to the presence of two peaks of pressure during the pipeline restarting. However, the restart pressure is found to be quite steady when the gas is injected at 60s and 65s, as only one peak of restart pressure is observed. In contrast, the propagation of restart pressures at WBT 32°C as illustrated in Figure 4 is found to be quite steady, as only one peak of restart pressure is found for all gas injection duration investigated. The unsteady pattern of restarting process found at WBT 20°C could be due to non-uniform distribution of wax deposited in the test section pipe, either at the pipe wall or at the center. As highlighted by Chala et al. (Girma T. Chala, Sulaiman, Japper-Jaafar, Kamil Wan Abdullah, & Mior Mokhtar, 2014), higher amount of voids are formed near the wall. This leads to uneven breakage of solid wax in the test section pipe during the restart. Furthermore, the restart pressure and gel strength also depends on the cooling rate under quiescent conditions, as suggested by Venkatesan et al. (Venkatesan et al., 2005).

In addition, the unsteady state is believed to be occurring within the test section pipe itself, where the solid wax has not yet fully disintegrated, due to its inhomogeneous wax formation distribution in the pipeline. As highlighted by Lee et al. (H. S. Lee, Singh, Thomason, & Fogler, 2008), the cooling rate of wax near the wall is faster than the center of pipeline, hence, the size and shape of the wax crystals deposited near the wall of the pipe will be different from those located at the center of the pipeline. In terms of cooling rate, the lowest WBT, 20°C recorded the lowest cooling rate, 0.2835°C/minute, whereas the highest WBT, 32°C recorded the highest cooling rate, 0.2980°C/minute. As the cooling rate is increased, the wax crystal size decreases, which leads to reduction in the interconnectivity of wax-crystal structure network, as well as increment in the number density of crystals. This results to the enhancement of adhesive strength, as the needlelike crystals allow larger effective surface area at the interface between the wax gel and wall, as stated by Greiner et al. (Greiner, Del Campo, & Arzt, 2007). In addition, Cheng et al. (Cheng, Boger, & Nguyen, 2000) also highlighted that larger wax particles and more agglomeration between particles are expected for slower cooling rates. During a static cooling condition, the waxy crude oil experiences thermal shrinkage, and naturally occurring gas voids form within the waxy crude oil gels. These gas voids offer a compressibility effect and hence can ease the pipeline restart process. As the duration of the gas injection prolongs, this implies that the volume of nitrogen gas is greater. The existence of larger gas voids within the pipeline facilitates the gelled waxy crude oil to mobilise, as more space are offered, consequently the gelled waxy crude oil would compress more during the pipeline restart operation, as stated by Sulaiman et al. (Sulaiman et al., 2017). Eventually, the presence of gas voids supports the disintegration of the gelled waxy crude oil that clogged the pipeline.

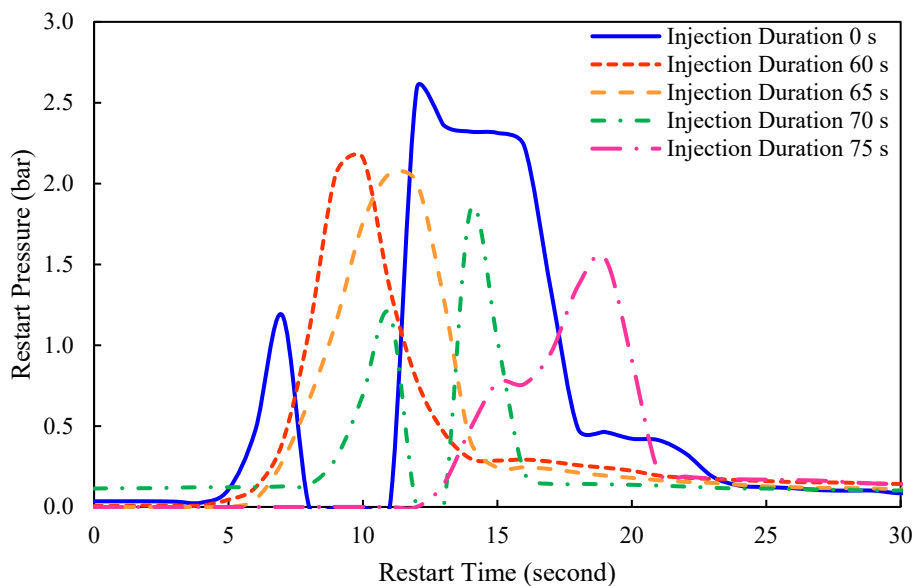


Figure 3. Restart pressure vs. restart time for WBT 20°C

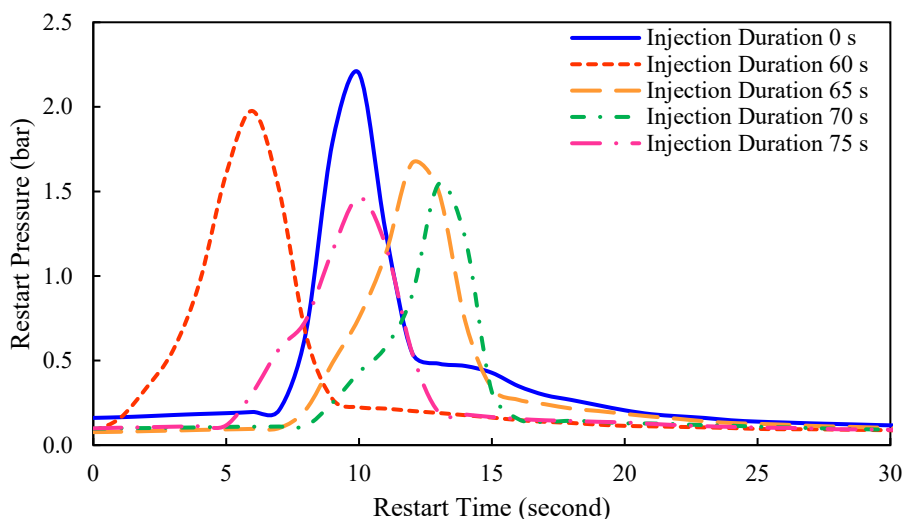


Figure 4. Restart pressure vs. restart time for WBT 32°C

## 5. Conclusion

Experimental investigation of the effect of water bath temperature on the cooling time of waxy crude oil in a pipeline is conducted in this study. Then, a different gas injection duration was introduced in the subsequent experiment to examine its effect on the restart pressure of waxy crude oil pipeline at WBT 20°C and WBT 32°C. The experiments were performed using a waxy crude oil flow loop rig. It is found that as the water bath temperature increases, the cooling time decreases, and the cooling rate increases. The longest cooling time, 3175s is found when WBT is decreased to 20°C, whereas the shortest cooling time, 604s is found when WBT is decreased to 32°C. In contrast, the slower cooling rate, 0.2835°C/minute is obtained at WBT 20°C, whereas the faster cooling rate, 0.2980°C/minute is achieved at WBT 32°C. When gas is injected into the waxy crude oil pipeline, it is observed that the restart pressure is inversely proportional with the gas injection duration. The highest restart pressure, 2.584 bar and 2.199 bar are recorded for WBT 20°C and WBT 32°C, respectively, for the case of no gas injection. The lowest restart pressure, 1.462 bar is attained at WBT 32°C with 33.52% reduction when gas is injected for 75s. Likewise, for WBT 20°C, the lowest restart pressure, 1.538 bar is achieved with 40.48% reduction when the pipeline is injected for a duration of 75s. Overall, the lowest temperature, WBT 20°C yields to the longest cooling time and slower cooling rate, and higher restart pressure. The highest temperature, WBT 32°C yields to the shortest cooling time and faster cooling rate, and lower restart pressure. The longer gas injection duration implies that greater volume of gas is injected into the pipeline



system. Hence, more voids are present and yields to higher compressibility to the gelled waxy crude oil within the pipeline.

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## References

- Abd Karim, R., Dahlan, M. S., Nordin, K. A., & Noor, H. M. *Successful application of six key elements in integrating people and technology toward quality achievements of Angsi field development team*. Paper presented at the SPE Annual Technical Conference and Exhibition. (2006).
- Agil, N. A. M., Mohd Saaid, I., Ibrahim, J. M., & Harun, M. F. *Utilizing acidized NH<sub>2</sub> for mitigating formation damage and improving oil recovery: Case Study of Penara Field, Malaysia*. Paper presented at the SPE Symposium on Improved Oil Recovery. (2008).
- Aguiar, J. I., Nerris, A. A., & Mahmoudkhani, A. *Can Paraffin Wax Deposit Above Wax Appearance Temperature? A Detailed Experimental Study*. Paper presented at the SPE Annual Technical Conference and Exhibition. (2020).
- Ajienka, J., & Ikoku, C. The effect of temperature on the rheology of waxy crude oils. (1991).
- Ajienka, J., & Ikoku, C. Criteria for the design of waxy crude oil pipelines: maximum pump (horsepower) pressure requirement. *Journal of Petroleum Science and Engineering*, 13(2), 87-94. (1995).
- Alade, O. S., Hassan, A., Mahmoud, M., Al-Shehri, D., & Al-Majed, A. Novel Approach for Improving the Flow of Waxy Crude Oil Using Thermochemical Fluids: Experimental and Simulation Study. *ACS omega*, 5(8), 4313-4321. (2020).
- Alnaimat, F., & Ziauddin, M. Wax deposition and prediction in petroleum pipelines. *Journal of Petroleum Science and Engineering*, 184, 106385. (2020). doi:<https://doi.org/10.1016/j.petrol.2019.106385>
- Barry, E. Pumping non-Newtonian waxy crude oils. *J. Inst. Pet.*, 57(554), 76-85. (1971).
- Borghini, G.-P., Corraera, S., Merlini, M., & Carniani, C. *Prediction and scaleup of waxy oil restart behavior*. Paper presented at the International Symposium on Oilfield Chemistry. (2003).
- Chala, G. T., Shaharin, A. S., Azuraian, J.-J., & Wan Ahmad Kamil, W. A. Investigation of convective heat transfer coefficient and initial temperature of waxy crude oil on the formation of voids. *International Journal of Automotive and Mechanical Engineering*, 13(3), 3754-3762. (2016).
- Chala, G. T., Sulaiman, S. A., & Japper-Jaafar, A. Flow start-up and transportation of waxy crude oil in pipelines-A review. *Journal of Non-Newtonian Fluid Mechanics*, 251, 69-87. (2018). doi:<https://doi.org/10.1016/j.jnnfm.2017.11.008>
- Chala, G. T., Sulaiman, S. A., Japper-Jaafar, A., & Abdullah, W. A. K. W. Effects of cooling regime on the formation of voids in statically cooled waxy crude oil. *International Journal of Multiphase Flow*, 77, 187-195. (2015). doi:<https://doi.org/10.1016/j.ijmultiphaseflow.2015.08.016>
- Chala, G. T., Sulaiman, S. A., Japper-Jaafar, A., Kamil Wan Abdullah, W. A., & Mior Mokhtar, M. M. Gas void formation in statically cooled waxy crude oil. *International Journal of Thermal Sciences*, 86, 41-47. doi:<https://doi.org/10.1016/j.ijthermalsci.2014.06.034>
- Chang, C., Boger, D. V., & Nguyen, Q. D. The yielding of waxy crude oils. *Industrial & engineering chemistry research*, 37(4), 1551-1559. (1998).
- Cheng, C., Boger, D. V., & Nguyen, Q. D. Influence of Thermal History on the Waxy Structure of Statically Cooled Waxy Crude Oil. *SPE Journal*, 5(02), 148-157. (2000). doi:10.2118/57959-PA
- Davenport, T., & Somper, R. The yield value and breakdown of crude oil gels. *J. Inst. Pet.*, 57(554), 86-105. (1971).
- de Souza Mendes Paulo, R. Rheological Characterization of Waxy Crude Oils: Sample Preparation. *Energy & Fuels*. (2012).
- Ehsani, S., Haj-Shafiei, S., & Mehrotra, A. K.. Experiments and modeling for investigating the effect of suspended wax crystals on deposition from 'waxy' mixtures under cold flow conditions. *Fuel*, 243, 610-621. (2019) doi:<https://doi.org/10.1016/j.fuel.2019.01.089>
- El-Gendy, H., Alcoutlabi, M., Jemmett, M., Deo, M., Magda, J., Venkatesan, R., & Montesi, A. The propagation of pressure in a gelled waxy oil pipeline as studied by particle imaging velocimetry. *AICHE journal*, 58(1), 302-311. (2012).
- Ford, P., Ells, J., & Russell, R. Pipelining high-pour-point crude. Pt. 3. Frequent pigging helps move waxy crude below its pour point. *Oil Gas J. (United States)*, 63(19). (1965).
- Greiner, C., Del Campo, A., & Arzt, E. Adhesion of bioinspired micropatterned surfaces: effects of pillar radius, aspect ratio, and preload. *Langmuir*, 23(7), 3495-3502. (2007).

- Hosseini-pour, A., Japper-Jaafar, A. B., & Yusup, S. The Effect of CO<sub>2</sub> on Wax Appearance Temperature of Crude Oils. *Procedia Engineering*, 148, 1022-1029. (2016). doi:<https://doi.org/10.1016/j.proeng.2016.06.580>
- Japper-Jaafar, A., Bhaskoro, P. T., Sean, L. L., Sariman, M. Z., & Nugroho, H. Yield stress measurement of gelled waxy crude oil: Gap size requirement. *Journal of Non-Newtonian Fluid Mechanics*, 218, 71-82. (2015). doi:<https://doi.org/10.1016/j.jnnfm.2015.02.001>
- Kechut, N. I., Nadeson, G., Ahmad, N., & Raja, D. *Evaluation of CO<sub>2</sub> gas injection for major oil production fields in malaysia-experimental approach case study: Dulang field*. Paper presented at the SPE Asia Pacific Improved Oil Recovery Conference. (2001).
- Lee, H. Computational and rheological study of wax deposition and gelation in subsea pipelines [Ph. D. thesis]. *Dept. of Chemical Engineering, University of Michigan*. (2008).
- Lee, H. S., Singh, P., Thomason, W. H., & Fogler, H. S. Waxy Oil Gel Breaking Mechanisms: Adhesive versus Cohesive Failure. *Energy & Fuels*, 22(1), 480-487. (2008). doi:10.1021/ef700212v
- Liu, G., Chen, L., Zhang, G., Chen, Z., Hao, Y., Dong, P., & Liu, J. Experimental study on the compressibility of gelled crude oil. *SPE Journal*, 20(02), 248-254. (2015).
- Luthi, I. F. *Waxy crude oil characterization and experimental study of the restart of a line blocked with gelled waxy crude*. Paper presented at the SPE Annual Technical Conference and Exhibition. (2013).
- Makogon, T. Y. *Handbook of multiphase flow assurance*: Gulf Professional Publishing. (2019).
- Mendes, R., Vinay, G., & Coussot, P. Yield stress and minimum pressure for simulating the flow restart of a waxy crude oil pipeline. *Energy & Fuels*, 31(1), 395-407. (2017).
- Nguyen, D. A. *Fused chemical reactions to remediate paraffin plugging in sub-sea pipelines*: University of Michigan. (2004).
- Perkins, T., & Turner, J. Starting behavior of gathering lines and pipelines filled with gelled Prudhoe Bay oil. *Journal of Petroleum Technology*, 23(03), 301-308. (1971).
- Rehan, M., Nizami, A.-S., Taylan, O., Al-Sasi, B. O., & Demirbas, A. Determination of wax content in crude oil. *Petroleum Science and Technology*, 34(9), 799-804. (2016).
- Rønningsen, H. P. Rheological behaviour of gelled, waxy North Sea crude oils. *Journal of Petroleum Science and Engineering*, 7(3-4), 177-213. (1992).
- Sestak, J., Charles, M., Cawkwell, M., & Houska, M. (1987). Start-up of gelled crude oil pipelines. *Journal of pipelines*, 6(1), 15-24.
- Settouti, N., Ruer, J., Muguerra, P., & Spudic, D. Station for heating fluids flowing through a network of submarine pipelines. In: Google Patents. (2020).
- Sulaiman, S. A., Biga, B. K., & Chala, G. T. Injection of non-reacting gas into production pipelines to ease restart pumping of waxy crude oil. *Journal of Petroleum Science and Engineering*, 152, 549-554. (2017).doi:<https://doi.org/10.1016/j.petrol.2017.01.046>
- Sulaiman, S. A., Chala, G. T., & Zainur, M. Z. Experimental investigation of compressibility of waxy crude oil subjected to static cooling. *Journal of Petroleum Science and Engineering*, 182, 106378. (2019). doi:<https://doi.org/10.1016/j.petrol.2019.106378>
- Theyab, M., & Yahya, S. Introduction to wax deposition. *Int J Petrochem Res*, 2(1), 126-131. (2018).
- Venkatesan, R., Nagarajan, N. R., Paso, K., Yi, Y. B., Sastry, A. M., & Fogler, H. S. The strength of paraffin gels formed under static and flow conditions. *Chemical Engineering Science*, 60(13), 3587-3598. (2005). doi:<https://doi.org/10.1016/j.ces.2005.02.045>
- Verschuur, E., Hartog, A., & Verheul, C. Effect of Thermal Shrinkage and Compressibility on Yielding of Gelled Waxy Crude Oils in Pipelines. *Journal of the Institute of Petroleum*, 57(555), 131-+. (1971).
- Vinay, G., Wachs, A., & Frigaard, I. *Start-up of gelled waxy crude oil pipelines: a new analytical relation to predict the restart pressure*. (2009, 2009).
- Yao, Z., Zhang, Y., Zheng, Y., Xing, C., & Hu, Y. Enhance flows of waxy crude oil in offshore petroleum pipeline: A review. *Journal of Petroleum Science and Engineering*, 208, 109530. (2022).

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