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Effect of Crude Oil and Nitrogen Gas Flow Rates on the Time Taken for Flow Initiation of Waxy Crude Oil

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Abstract: Transportation of waxy crude oil in a production pipeline often encountered flow assurance issues, such as wax deposition. In a case where pipeline shutdown is needed, wax deposit is likely to form within the pipelines, which leads to operational complexity during the restart phase. Commonly, crude oil restarts to flow after a significantly high restart pressure is pumped longer than is necessary. This is due to the physical hindrance caused by the solid wax, which requires additional pressure to disintegrate it before achieving a steady crude oil flow. This study aims to investigate the effect of crude oil and nitrogen gas flow rates on the time taken for crude oil flow initiation using a flow loop rig, which is connected to a nitrogen gas injection system. The nitrogen gas was injected into the test section pipeline at predetermined flow rates within specified periods. After 45 min of static cooling, the crude oil gear pump is switched on to build sufficient pressure to initiate the waxy crude oil flow in the pipeline. Additionally, a statistical analysis by the response surface methodology was also performed by Minitab® 19 software. Results show that the maximum reduction in flow initiation is 73.7% at 5 L/min of crude oil and 1 L/min of nitrogen gas. This study reveals that the presence of nitrogen gas improved the pipeline restart phase by minimizing both restart pressure and time taken for flow initiation.

Keywords: wax deposition; waxy crude flow loop; nitrogen gas; flow initiation

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1. Introduction

Over the past two decades, there was a continual increment in demand for crude oil on a global scale. In response to the fall of conventional light crude oil production, more heavy crude oil is being extracted. Inevitably, this creates new technological challenges at every stage of the process, from extraction to transportation and processing [1]. Since its first production in the 1940s, the crude oil production rate increased rapidly due to the depletion of production at onshore fields [2]. During the transportation of crude oil from reservoirs to production surface facilities, operators faced challenges with the existence of wax deposition [3]. There was a previous report where crude oil transportation from an offshore oil rig to floating production storage and offloading (FPSO) was put to a halt due to wax accumulation [4].

At reservoir condition, the viscosity of a fluid is ideally not affected by temperature, and wax molecules are believed to emerge as the liquid phase of crude oil in the Newtonian region. These wax molecules crystallize and solidify when exposed to cold temperatures [5]. Wax deposition primarily results in a sharp reduction in wax solubility value. These wax molecules are described as lump, and macro compounds would subsequently harden and produce a gel, resulting in a reduction in pipelines cross sectional area [6]. Waxes are n-paraffin (C12–C35) chemical molecules that have a propensity to accumulate on the internal surface of pipeline walls. The main reason is because the temperature of waxy crude oil drops below the wax appearance temperature (WAT) after it leaves the reservoir and passes through a subsea pipeline laying on the cold ocean floor caused by subsequent heat loss to the surroundings [5,7–9].

According to Misra et al. [10], factors influencing wax deposition in waxy crude oil include crude oil flow rate, cooling rate, surface characteristics, and operating conditions. Furthermore, thermal history, pressure, time, and crude oil composition were also reported influencing the wax depositions [11–17]. In a study performed by Creek et al. [15], it was observed that there was a reduction in the wax thickness as the flow rates were increased. A similar observation was also found by Wang et al. [16], in which flow rate had a substantial impact on lowering the wax deposition rate in waxy crude oil. Theyab [17] presented that as the flow rate was intensified to turbulent regimes, wax deposition was found to be reducing due to the increment of shear dispersion.

When an emergency shutdown or a scheduled pipeline maintenance takes place, the transportation of crude oil in the pipeline is halted for a certain period of time. The static condition triggers wax nucleation to occur due to a temperature difference between the pipeline and the seabed environment. Consequently, the formed wax crystals agglomerate between themselves and form bigger, heavier molecules that start to deposit on the inner surface of the pipeline. This leads to pipe blockage and difficulty during the restarting phase of the production pipeline since additional energy is required to displace the coagulated wax that obstructed the flow. Furthermore, time taken for flow initiation (an instance where fluid resumes flowing) could be increasing when more wax blockage happens. Unnecessary delay during flow initiation within the pipeline impacted the upstream production operation efficiency. This leads to the demand for higher pump capacity [18,19]. The typical equation used to measure the amount of pressure required to restart a flow is given by Equation (1). The equation involves a force balance between the yield stress and the boundary conditions [20–24].

$$\Delta P_{min} = \frac{4\tau_w L}{D} \tag{1}$$

where ΔP_{min} is minimum required pressure, τ_w is shear stress, L is length of pipe, and D is diameter of pipe. Margarone et al. [25] revealed that a restart pressure calculation using this conventional equation often leads to overestimation and hence results in unnecessary additional pipeline insulation and pumping station requirements. This is because the equation does not consider the properties of non-Newtonian gelled crude oil when forecasting a precise restart pressure [26]. Further, other factors, such as thermal shrinkage, the subsequent gas voids created within the gelled crude oil, and the assumptions that the waxy crude oil is present as a single, incompressible fluid, lead to the overprediction of pumping pressure and pipeline dimensions. The minimum required restart pressure is hypothesized to be lower than the calculated value, due to the shrinkage-induced flow [27].

Nitrogen gas is an inert gas and makes up 78.1% by volume of the atmosphere. In oil and gas application, nitrogen gas was used in pressure purging and testing applications [9,28,29], as well as in supporting various operations, such as drilling, cementing, and well completion. Additionally, nitrogen gas was utilized as a wax dispersant additive in paraffinic gas oils. In a study performed by El-Gamal et al. [30], the existence of polar nitrogen/oxygen-containing functional groups is the origin of induced dipole attractive forces in the n-paraffin molecules of crude oil during crystallization. Consequently, a secondary attractive force is formed that has a dispersing effect of wax dispersant. In another study by Struchkov et al. [31], nitrogen gas was also found to reduce the WAT in oil. Nevertheless, investigation on the effect of nitrogen gas in flowing waxy crude oil at various rates remains limited. Hence, this study aims to investigate the effects of crude oil and nitrogen gas flow rates on the time taken for flow initiation using a flow loop system.

2. Materials and Methods

2.1. Materials and Equipment

Table 1 shows the chemical properties of oil sample used in this study. The WAT is determined through the ASTM D3117, pour point temperature (PPT) is through ASTM D97, dynamic viscosity is measured using viscometer, and density is measured using the Coriolis flow meter. Figure 1 shows the schematic diagram of a flow loop system with a test section of 1.2 m in length and 5 cm in diameter.

Table 1. Chemical properties for waxy crude oil sample.

Chemical Properties	Data
WAT (°C)	38.5
PPT (°C)	36.0
Density (kgm^{-3})	850
Specific gravity	0.85
Dynamic viscosity (Pa.s)	0.002

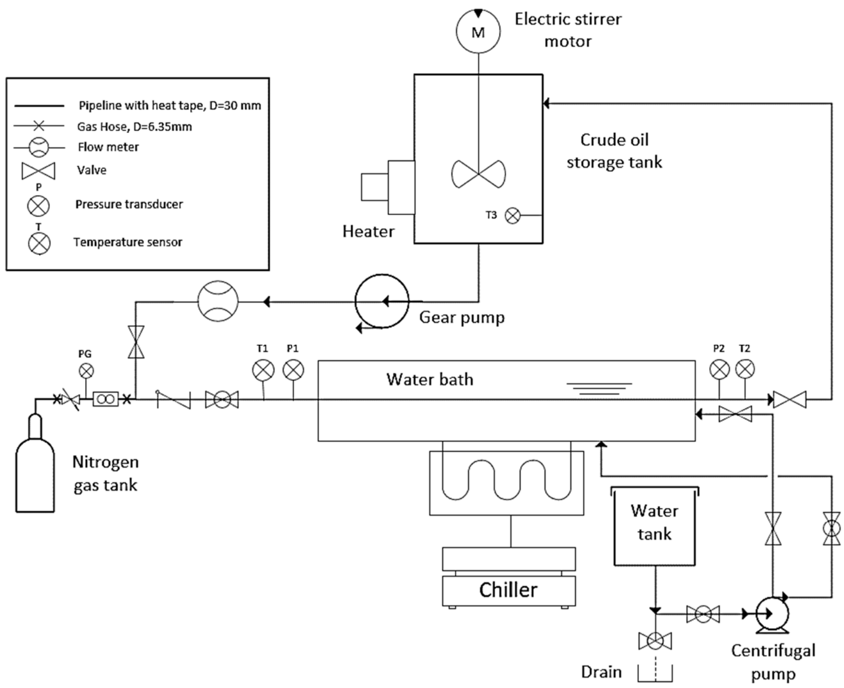

Figure 1. Schematic diagram of waxy crude oil flow loop system where the test section pipe is submerged in a water bath.

2.2. Experimental Techniques

General setting and operating conditions of the flow loop system are similar with published procedures [32,33]. Before any fresh cycle of investigation starts, the flow loop system needs to undergo pre-operation. Firstly, a heater that connects to a waxy crude oil storage tank is switched on. A set temperature is higher than the WAT of the crude oil to liquefy any waxes. Heater extension that coils around the pipelines (except the test section pipe) is also switched on to increase the temperature of crude oil inside the pipeline. After 5 min, an electric stirrer in the waxy crude oil storage tank is turned on to ensure homogeneous heating within the tank. This is to remove any past thermal behaviour history of crude oil. After ~30 min, a crude oil gear pump is switched on to have a steady flow of crude oil of 15 L/min. The flow loop system is now ready for the study. A chiller system is switched on to reduce the water bath temperature to 26 °C (mimicking seawater temperature). After several minutes of steady flow was achieved, the crude oil volume flow rate was decreased to a predetermined value, and nitrogen gas was injected into the inlet of the test section pipeline before the crude oil gear pump was switched off entirely. This was to replicate the pipeline shutdown condition at field.

The main valve of the nitrogen gas tank was opened by turning its knob in an anti-clockwise direction. The nitrogen gas pressure regulator valve was adjusted to a specified pressure (3 bar). The gas flow meter, which was attached to both the outlet port of the nitrogen gas pressure regulator and the inlet port of the test section pipe, was adjusted to specified flow rates (1 L/min, 2 L/min, and 3 L/min). The check valve at the inlet port of the test section pipe was opened for a specified time (70 s) to let the nitrogen gas flows into the test section pipe. After 70 s, the check valve was closed. Then, both gas flow meter and nitrogen gas pressure regulator valve were closed by turning their knobs in a clockwise direction to 0 L/min and 0 bar, respectively. Lastly, the main valve of the nitrogen gas tank was closed fully.

Then, the pipeline underwent the static cooling phase for 45 min to allow the waxy crude oil to be solidified in the pipeline. After 45 min, the crude oil gear pump was switched on to build up the pressure to displace the gelled crude oil within the pipeline for a restart process. The responses from the experiment were retrieved by a data logger connected to a computer. The investigated crude oil flow rates are 1–5 L/min and nitrogen gas flow rates are 1–3 L/min.

2.3. Description of Experimental Design

Minitab® 19 software was used in the design of experiment (DoE) where response surface methodology (RSM) and the Box–Behnken design (BBD) techniques were selected. The RSM is a design tool that offers a variety of statistical and mathematical methods for enhancing and expanding process optimization [34]. The term "optimization" was widely used in analytical chemistry as a method of identifying the circumstances under which to execute a procedure in order to get the best possible result [35]. The reaction of the system under study may be influenced by a wide range of factors, and it is virtually impossible to isolate and manage the insignificant contributions from each one. Therefore, it is important to choose the factors having the significant influence. To ascertain which of the various experimental variables and their interactions present more profound effects, screening designs should be carried out [36]. For this purpose, BBD is utilized due to its effectiveness and affordability. The BBD was applied to model the effect of gas injection duration, gas injection pressure, gas injection flow rate, and crude oil flow rate on the time taken for flow initiation of the waxy crude oil pipeline. Understanding the interactions between the factors is the main goal of the experimental design technique since it can aid in the optimization of the experimental parameters and give statistical models [37]. Table 2 displays the factors and their respective lower, middle, and upper limits used as inputs of the software.

Table 2. Parameters used in the BBD.

Parameters	Lower	Middle	Upper
Time taken for gas injection, s	60	70	80
Gas injection pressure, bar	1	3	5
Gas injection flow rate, L/min	1	2	3
Crude oil flow rate, L/min	1	3	5

3. Results and Discussion

3.1. Effect of Crude Oil Flow Rate on Time Taken for Flow Initiation

Figure 2 shows the time taken for flow initiation at various waxy crude oil and nitrogen gas flow rates. Under static condition, it is found that waxy crude oil initiated its flow mobility in 38 s. Meanwhile, under flowing conditions (1 L/min to 5 L/min) and with the presence of gas, results reveal that the time taken to initiate the flow is faster than before. The fastest flow initiation is at 5 L/min crude oil, the result of which is highly expected since flowing fluid will impose less friction force to the surface wall of pipelines. However, the time taken for flow initiation is slightly increased when nitrogen gas is introduced.

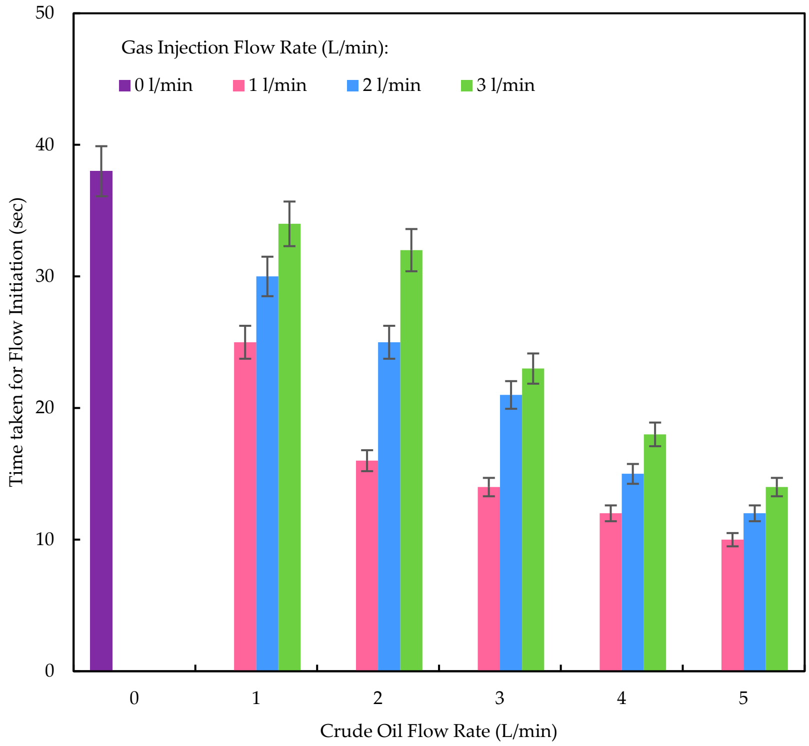

Figure 2. Time taken for flow initiation vs. crude oil flow rate at different gas injection flow rate.

At 1 L/min nitrogen gas, results show that the reduction in flow initiation is by 34.2%, 57.9%, 63.2%, 68.4%, and 73.7% at 1 L/min, 2 L/min, 3 L/min, 4 L/min, and 5 L/min crude oil, respectively. The effect of nitrogen gas flow rate was found to slightly increase the time taken up to 1%. In general, when no gas was injected, the restart pressure was overestimated, hence leading to a longer time for restart to take place to shatter the wax blockage within the pipeline.

Figure 3a–c show the real-time measurement of the restart pressure recorded over the time of the flow loop. The highest peaks of the pressure propagation plot signify the time taken for flow initiation of the waxy crude oil and its corresponding restart pressure. Overview of the real-time measurements revealed that the restart pressure is lower than the one when there is no gas injection. For the condition of no gas injection, 38 s is required for the waxy crude oil to start flowing. There was a no-flow period of 4 s observed before flow resumed. The intermittent flow implies that the restart of the pipeline was disturbed when there was no aid of nitrogen gas injection available. Figure 3a shows the restart pressure measurement at 1 L/min nitrogen gas and 1 to 5 L/min crude oil. The number that appears at the top peak shows the time that generated the highest restart pressure for each crude oil flow rate, hence the number reflects the time taken for flow initiation for the respective condition. The lowest reduction in flow initiation was found at 1 L/min crude oil where the time taken for flow initiation reduced by 34.2%. As the crude oil flow rate increases, the time taken for flow initiation is expedited. The maximum reduction in flow initiation was found at 5 L/min crude oil, which is 73.7%. Notably, the flow takes only 10 s to be re-initiated to flow in the flow loop.

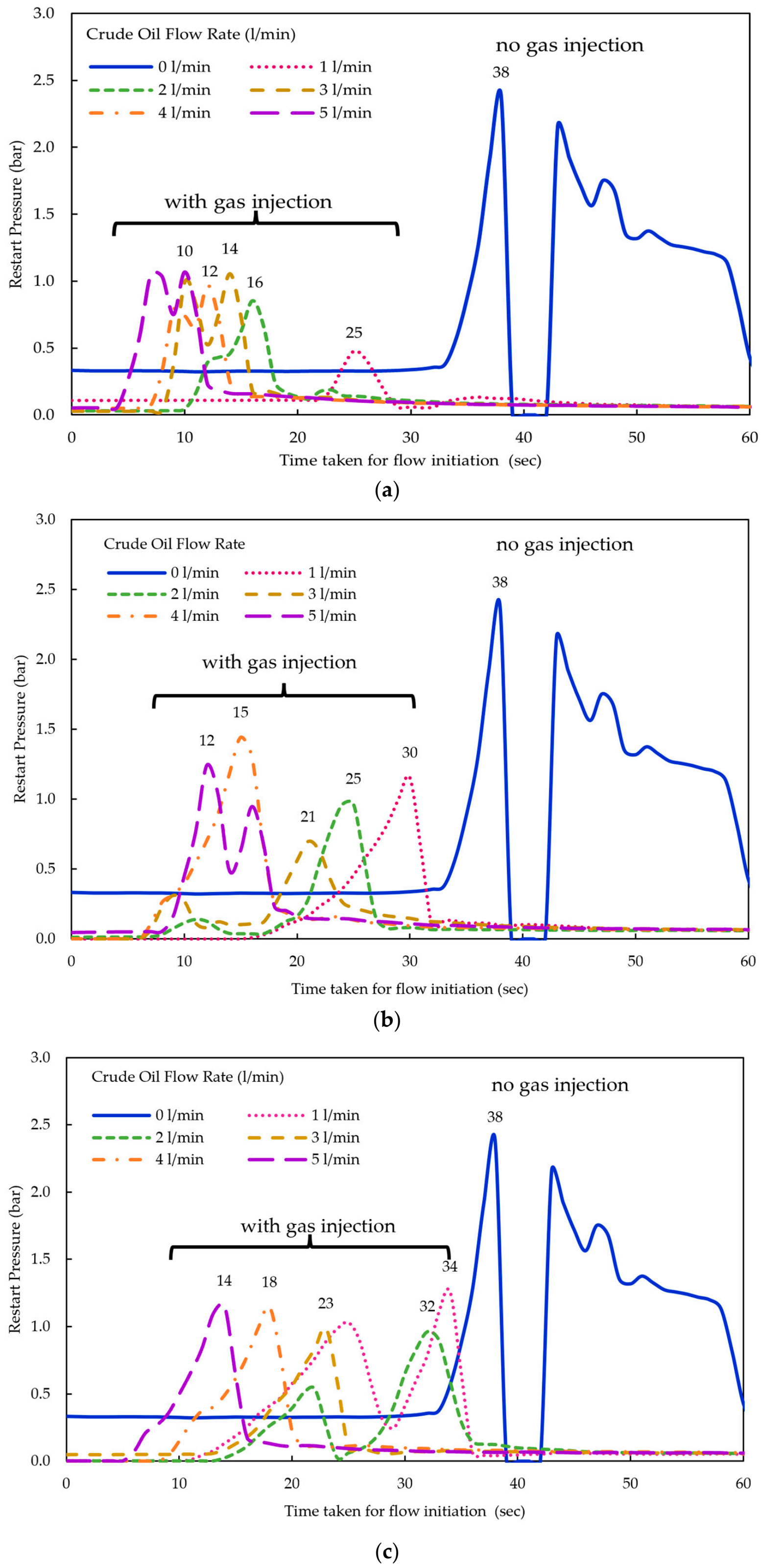

Figure 3. Variation in time taken for flow initiation of waxy crude oil pipeline at various gas injection flow rates (**a**) 1 L/min, (**b**) 2 L/min, and (**c**) 3 L/min.

A similar trend was observed in Figure 3b,c, where the time taken for flow initiation was reduced as the crude oil flow rate increased. Analysis is conducted for both figures at the same time. Here, we found that at 1 L/min crude oil, the time taken is reduced by 21.1%

and 10.5% at 2 L/min and 3 L/min gas flow rate, respectively. Meanwhile at 5 L/min crude oil, the time taken is further reduced, which is by 68.4% and 63.2% at 2 L/min and 3 L/min gas flow rate, respectively. The finding is in agreement with work from Junyi and Hasan [38], who revealed that wax deposition decreased as the flow rate in the waxy crude oil pipeline was enhanced. When wax deposition was decreased, the flow initiation was at ease, since there were less restrictions of solid blockage to be overcome during the pipeline restart. Consequently, this led to a shorter time taken for flow initiation. The research findings from Kelechukwu et al. [39] also support the results of this study, where wax deposition was reduced as the flow rate was increased to turbulence flow. In addition, Cabanillas et al. [40] highlighted that the thickness of the deposited wax declined as the flow rate intensified. Additionally, the discovery is consistent with findings of past studies by Mahto and Kumar [41], who summarized that the wax precipitation increased as the flow rate decreased in the laminar flow, due to the expansion of accessibility of the solid wax particles to deposit on the inner surface of the pipeline.

Compressibility effect also plays a role in reducing the time taken for flow initiation. In a study by Sulaiman et al. [42] on the compressibility effect of waxy crude oil during a static cooling, it was observed that greater piston stroke was produced by higher compression pressure, especially in the first 20 s following compression. This implies that disintegration of solid wax within the pipeline occurs during the first 20 s. As reported by Frigaard et al. [43], the presence of gas voids contributes to the compressibility effect, which lessens the time needed to restart the flow as well as reduces the pressure drop at the inlet section of the pipe. Cawkwell and Charles [44] added that the gelled crude oil were able to be displaced due to the compressibility of the gel. Furthermore, the restart pressure can be reduced as the compressibility increases [44,45]. When this occurs, the time taken for flow initiation can be minimized, hence increasing the production efficiency.

3.2. Model Summary for Time Taken for Flow Initiation

The effect of the gas injection duration, gas injection pressure, gas injection flow rate, and crude oil flow rate on the time taken for flow initiation was examined by the Box–Behnken design (BBD) technique. The variables' interaction amongst themselves and individual effects on the responses were evaluated by Analysis of Variance (ANOVA). The significance of each independent variable (factors) was determined by their respective probability values, i.e., p-value and f-value. The p-value, which is less than or equal to 0.05 for a 95% confidence level indicates how closely the results match those of the actual experiments. The f-values compare the variables both within and between the model, but it must be greater [46]. A p-value of less than 0.05 suggests that the factor is statistically significant, whereas a p-value of more than 0.05 implies that the factor is not statistically significant [47]. In the response surface regression for time taken for flow initiation, the gas injection flow rate and crude oil flow rate were found to be significant factors, with p-values of 0.011 and 0.001, respectively. The f-values of gas injection flow rate and crude oil flow rate were 9.11 and 19.93, respectively. A low p-value and high f-value signifies that the model is significant. This finding is supported by a previous similar study conducted by Nachiyar et al. [48]. Table 3 displays the model summary for time taken for flow initiation by the response surface regression.

Table 3. Model summary for time taken for flow initiation.

Parameter	p-Value	f-Value
Gas injection duration	0.502	0.48
Gas injection pressure	1.000	0
Gas injection flow rate	0.011	9.11
Crude oil flow rate	0.001	19.93

3.3. Correlation between Input Factors and Time Taken for Flow Initiation

The correlation between input factors and time taken for flow initiation of the waxy crude oil pipeline was analysed by maintaining other input factors constant at a mean point. Figure 4a–d displays the main effect plot for the time taken for flow initiation. The mean time taken for flow initiation fluctuated from 18.7 s, 17.8 s, to 20.5 s as the gas injection duration increased from 60 s, 70 s, to 80 s, respectively. Similarly, there was also a slight fluctuation observed as the gas injection pressure changed. The mean time taken for flow initiation increased from 18 s to 19 s as the gas injection pressure increased from 1 bar to 3 bar. When the gas injection pressure further increased to 5 bar, the mean time taken for flow initiation decreased to 18 s. The ambiguous trend of these factors; the gas injection duration and the gas injection pressure; may be due to inhomogeneous wax deposition within the pipeline itself [49]. In contrary, gas injection flow rate showed a significant response on the mean time taken for flow initiation. As the gas injection flow rate increased, the mean time taken for flow initiation increased too. The mean times taken for flow initiation recorded were 13.5 s, 19.5 s, and 21.5 s at gas injection flow rate of 1 L/min, 2 L/min, and 3 L/min, respectively.

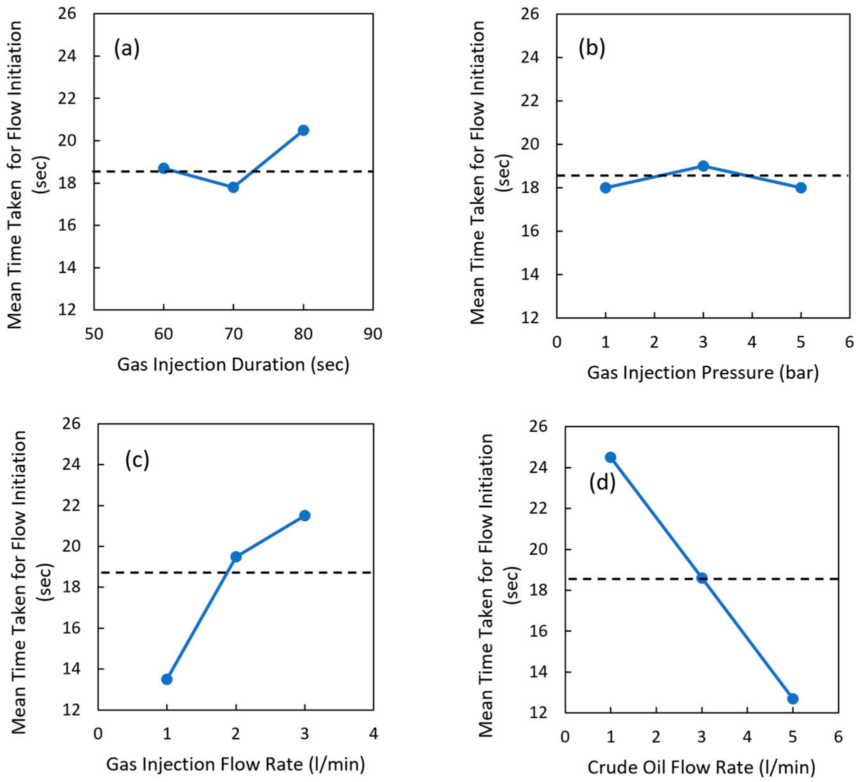

Figure 4. Main effects plot for time taken for flow initiation for different factors: (**a**) gas injection duration, (**b**) gas injection pressure, (**c**) gas injection flow rate, and (**d**) crude oil flow rate.

Notably, a different trend was found for the crude oil flow rate, where the mean time taken for flow initiation was inversely proportional with the crude oil flow rate. The longest time taken for flow initiation (i.e: 24.5 s) was found at 1 L/min, followed by 18.6 s at 3 L/min and 12.7 s at 5 L/min. Among the four input factors, the crude oil flow rate demonstrated the most significant response in the mean time taken for flow initiation, followed by gas injection flow rate, gas injection duration, and lastly, gas injection pressure factor. Crude oil flow rate contributed to the most significant reduction in the mean time taken for flow initiation, by 48.2%, whereas gas injection flow rate contributed to an increment of 37.2% in the mean time taken for flow initiation. The statistical analysis from the BBD technique reproduced the quantitative experiment results. Ultimately, the conventional equation used to calculate the minimum pressure of the restart pump is overestimated since gas voids formation, thermal shrinkage, and compressibility is ignored.

4. Conclusions

In this research study, investigation on the effect of different crude oil and nitrogen gas flow rates on the time taken for flow initiation of waxy crude oil was performed. The quantitative experiments were carried out using a flow loop system, which is connected to a nitrogen gas injection system. A statistical analysis by the RSM was also conducted by the Minitab® 19 software to study the effects of four factors, i.e., gas injection duration, gas injection pressure, gas injection flow rate, and crude oil flow rate on the time taken for flow initiation of the waxy crude oil in the pipeline. When there was no gas injected into the pipeline, the time taken for crude oil sample to flow was 38 s. It was discovered that the intrusion of nitrogen gas into the waxy crude oil pipeline slightly eased the restart process by minimizing the time taken for flow initiation. As the crude oil flow rate increases, the time taken for flow initiation decreases. On the contrary, the time taken has a slight increment when nitrogen gas is introduced. The maximum reduction in flow initiation is 73.7% at 5 L/min of crude oil and 1 L/min of nitrogen gas. Only 10 s were needed for flow of waxy crude oil to take place, which saved time and could enhance the production efficiency. This is due to the turbulence effect of the crude oil as it flows at a higher rate, which eventually lessens the amount of wax deposition thickness within the pipeline. This tremendously saved the amount of time required to restart the pipeline that was coagulated with the solid wax. The most significant factor that affected time taken for flow initiation was the crude oil flow rate, with a p-value of 0.001. Based on the correlation study between the input factors and time taken for flow initiation, the findings were consistent with the outcomes of the quantitative experiments. The flow loop system is able to record the time taken for flow initiation, as well as the pressure needed to restart a flow. For future investigation, the amount of wax that deposited is suggested to be calculated as well for correlation studies.

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