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Flow Assurance for Paraffinic Classified Crude Oil Using Water Heating Boiler Metode in Field Sepanjang East Java

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ABSTRACT - Field Development and Drilling of New Wells in Indonesia continues to be carried out with the aim of maintaining and increasing oil and gas production. When transporting crude oil from the well to the storage tank, special handling is required. The transportation of crude oil through pipelines has the potential for several issues, one of which is wax deposition. This study aims to analyze the causes of wax deposition in pipelines, analyze the effect of pipe diameter on wax deposition, analyze the impact of using insulation on wax deposition, and analyze the influence of insulation thickness on wax buildup. Flow assurance is essential to determine the optimum pipeline size based on the results of reservoir well tests, considering operating pressure and flow rate. If the pipeline size is increased, pressure and temperature will drop. This could cause the fluid not to reach its destination and may result in the formation of hydrates, wax, and asphaltenes inside the pipeline. On the other hand, if the pipeline size is too small, the pressure and temperature will be very high. This will require a thicker pipeline design and is likely to cause significant thermal expansion. Flow assurance is a term that refers to the process of maintaining the flow of fluids (water, gas, oil) from the well to the pipeline transfer point using chemical treatments and engineering approaches. The basis of flow assurance lies in fluid chemistry (composition, pressure, and temperature) and fluid hydraulics (ratios, production rates, and topography)

Keywords: flow assurance, flowline, paraffinic-paraffinic, wax, crude handling, oil transfer, olga simulation, Production Facilities, hot water boiler

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1. Introduction

Field development and the drilling of new wells in Indonesia continue to be carried out with the aim of maintaining and increasing oil and gas production. Transporting crude oil from the well to the storage tank requires special handling. The transportation of crude oil through pipelines has the potential for several issues, one of which is wax deposition. This study aims to evaluate the effectiveness of hot water flushing as a method for mitigating wax deposition in the pipeline segment.

Flow Assurance is a term that refers to the process of maintaining the flow of fluids (water, gas, oil) from the well to the pipeline delivery point using chemical treatments and engineering approaches. The basis of flow assurance lies in fluid chemistry (composition, P, and T) and fluid hydraulics (ratio, production rate, topography).

Flow assurance is essential for determining the optimum flowline size based on the results of well reservoir tests under working pressure and flow rate.

If the pipe size is increased, increased heat loss due to greater surface area, which could lead to a temperature drop. If the pipe size is too small, pressure and temperature will be very high. This will result in a larger required pipe wall thickness and is expected to cause significant thermal expansion.

Based on the background described above, the research problem can be formulated as follows. Oil production that carries a higher level of risk, difficulty, and cost is a fitting example when discussing flow assurance. Wax deposition is one of the major challenges in oil and gas transportation systems, particularly in pipelines transporting waxy crude oil under low-temperature conditions, as it can significantly affect production performance and reduce the overall economic viability of the system (Carnahan 1989; Aiyejina et al., 2011).

Flow Assurance covers the entire source, process, facilities, and conditions that affect the successful flow of hydrocarbons from the reservoir to the processing or sales point, where sub-surface and surface aspects together determine the overall flow assurance design.

In general, the objective of this research is to develop a paraffinic-paraffinic oil analyze an existing one to optimize mitigation flowline system by utilizing crude assay analysis report data, fluid properties, reservoir characteristics, and well data. This model is expected to be able to estimate the maximum value of the flowline system method from the well to the production facility up to the delivery point.

The effectiveness of *hot water* is strongly influenced by operational parameters, including injection temperature, flushing duration, and flow characteristics. Therefore, an evaluation based on actual field data is essential to assess the effectiveness of this method in mitigating *wax deposition* and improving flow performance in pipeline systems (Bell et al., 2021).

Flow assurance research ensures sustainable and stable production, avoiding downtime caused by flow problems. Understanding the risks associated with fluid flow allows companies to take appropriate preventive action and better manage operational risk (Kiyangi et al., 2022). The specific objectives of this research include:

- Identifying the temperature drop that can result in wax deposition (Wax Appearance Temperature).
- Analyzing the performance of the production piping system to identify, at an early stage, the initial location where paraffinic wax deposition occurs.
- Identifying risks associated with fluid flow to enable the company to take appropriate preventive action and manage risk.

A flow assurance specialist must be able to design multiphase systems using equipment, methods, knowledge, and professional skill to ensure the safety and continuity of fluid production from the reservoir to the processing facility. Well production is a dynamic process in which oil and gas production is accompanied by an increasing, ongoing production of water from within the well. A well's production will be stopped once the cost of handling the produced water exceeds the economic value of the gas or oil being produced.

In multiphase flow, pressure drop is influenced by many parameters. All of these parameters need to be evaluated and calculated at every part of the production system. The following are the parameters that influence

the occurrence of pressure drop in a multiphase production system. In multiphase flow, the fluid phase will vary across different parts of the production system according to temperature, pressure, and flow rate.

Density is one of the parameters that influences pressure drop; a fluid with a larger liquid phase fraction will have a greater pressure drop value than a fluid with a larger gas phase fraction. This means that as a well is produced and water starts rising in addition to the oil/gas, pressure drop will increase and the production rate will decrease. Density in multiphase flow is a function of the three-phase flow rate, temperature, and pressure.

The length of the flowline system is an important parameter in some fields, particularly the distance from the subsea field to land or shore. Whether fluid phase separation and pressure boosting via pumps and compressors are needed must be evaluated in order to obtain sufficient pressure within the system. Velocity refers to the increase in flow rate, which results in an increase in pressure loss (pressure drop). Friction inside the pipe: for long pipes, the contribution of friction between the fluid and the pipe wall is a fairly influential parameter causing pressure loss.

Crude oil is a mixture of hydrocarbons (consisting of combinations of hydrogen and carbon atoms) that forms and occurs naturally within the earth's crust. In addition to hydrogen and carbon atoms, crude oil also contains impurity compounds such as sulfur, oxygen, and nitrogen bonded with hydrogen and carbon atoms, as well as a small amount of non-hydrocarbon compounds such as H₂S, CO₂, N₂, heavy metals, and water.

The physical properties of hydrocarbon deposits in a reservoir (whether in liquid, gas, or solid form) are determined by the composition of the hydrocarbon compounds and the reservoir's pressure and temperature. If the main components of the hydrocarbon are light hydrocarbon components or compounds with low molecular weight such as methane and ethane, the hydrocarbon will be in gas form under atmospheric conditions. If the hydrocarbon is dominated by heavy hydrocarbon components, it will be in liquid, semi-solid, or solid form under atmospheric conditions. The common term used for liquid hydrocarbon is petroleum or crude oil, while hydrocarbon in gas form is called natural gas. Crude oil can be classified as aromatic or paraffinic depending on which molecules dominate its composition. Crude oil dominated by paraffin molecules will yield very fine lubricating oils in its gas-oil fraction and paraffin wax from its residue. Conversely, if crude oil is dominated by aromatic molecules, the heavy fraction of the crude oil is used for pitch, roofing compounds, asphalt, and other compounds (Alwazzan et al., 2019).

Crude oil obtained from different oil reservoirs has very different characteristics. Some are black, heavy, and viscous like asphalt. Crude oil obtained from different oil reservoirs has very different characteristics. Some are black, heavy, and viscous like asphalt, while others are brown or nearly clear with low viscosity and low specific gravity. In general, crude oil has a lower density than water. The components contained in crude oil vary greatly and number in the thousands, but in terms of their constituent elements, almost all crude oils have roughly the same elements. Crude oil component (Table 1). Petroleum components are grouped according to oil fractions determined based on the boiling point range of the compounds contained in each oil fraction. Oil fractions (Table 2).

Table 1.
Crude oil component.

No	Element	Weight Percent
1	Carbon	84 – 87 %
2	Hydrogen	11 – 14 %
3	Sulfur	0.06 – 2.0 %
4	Nitrogen	0.1 – 2.0 %
5	Oxygen	0.1 – 2.0 %

Tabel 2.
Oil fractions based on boiling point.

No.	Petroleum Fraction	Boiling Point (°F)	Chemical Composition	Typical Applications
1	Hydrocarbon Gases	–	C ₁ –C ₂	Natural gas, fuel gas
2	Petroleum Ether (Ligroin)	Up to 160	C ₅ –C ₆	Solvents and cleaning agents
3	Gasoline	160–400	C ₆ –C ₁₂	Automotive fuel and industrial solvents
4	Kerosene	400–575	C ₁₂ –C ₁₆	Aviation fuel, heating fuel, and solvents
5	Heavy Gas Oil	850–1100	C ₁₅ –C ₂₀	Feedstock for lubricating oil production and bunker fuel
6	Residue	Above 1200	C ₂₀ +	Tar, asphalt, waxes, resins, roofing materials, and other heavy petroleum products

The Joule–Thomson equation, also referred to as the Joule–Kelvin equation, describes the temperature variation of a fluid as it undergoes expansion through a porous plug or throttling valve under thermally insulated conditions. The equation establishes the relationship between temperature change and pressure change during a constant-enthalpy (isenthalpic) expansion process. As the fluid flows through the pipeline, it experiences heat loss to the surrounding environment, resulting in a gradual decrease in fluid temperature. However, the cooling effect associated with gas expansion due to the Joule–Thomson phenomenon is not considered in the derivation of the following equation. For subsea pipelines, the surrounding environment is assumed to consist of seawater at a constant temperature. In contrast, for onshore pipelines sleep on ground, the ambient environment is assumed to be air at a constant temperature.

At a temperature of 51°C, which is above the pour point of the crude oil, the oil can be assumed to retain sufficient flowability under the given operating conditions. However, this condition does not necessarily indicate that the crude oil is free from the potential for wax deposition. Therefore, the Wax Appearance Temperature (WAT) and the rheological characteristics of the crude oil should also be considered to ensure adequate flow assurance during pipeline operation. The variables used in the following equation are defined as in Equation 1

$$q = UA\Delta T_{LMTD} \quad (1)$$

the temperature reduction of the fluid flowing through the pipeline can be described by the following Equation 2

$$q = mC_p (T_1 - T_2) \quad (2)$$

the logarithmic mean temperature difference (LMTD) for a pipeline segment with a length of L is given by Equation 3

$$\Delta T_{LMTD} = \frac{(T_1 - T_0) - (T_2 - T_0)}{\ln \frac{T_1 - T_0}{T_2 - T_0}} \quad (3)$$

under the assumption of a constant ambient temperature,

$$\Delta T_{LMTD} = \frac{T_1 - T_2}{\ln \frac{T_1 - T_0}{T_2 - T_0}} \quad (4)$$

applying the energy balance to a differential pipeline segment, the rate of heat loss from the flowing fluid is equal to the rate of heat transfer through the pipe wall

$$C_p(T_1 - T_0) = U\pi d(L) \frac{T_1 - T_2}{\ln \frac{T_1 - T_0}{T_2 - T_0}} \quad (5)$$

$$A = \pi d(L) \quad (6)$$

$$\ln \frac{T_1 - T_0}{T_2 - T_0} = \frac{U\pi d(L)}{mC_p} \quad (7)$$

$$\ln \frac{T_2 - T_0}{T_1 - T_0} = \frac{-U\pi d(L)}{mC_p} \quad (8)$$

$$T_2 = T_0 + (T_1 - T_0) \exp \left[\frac{-U\pi d(L)}{mC_p} \right] \quad (9)$$

2. Methodology

This research is quantitative in nature, using a process-data-based predictive modeling approach carried out through the collection and processing of fluid physical property data and production behavior characteristics.

This subsection explains the overall research design, from the data collection process and model development to the model validation process. This research uses a data-based associative and comparative design.

The research process began with the collection and validation of commissioning data and relevant operational data, including pressure, flow rate, temperature, flushing duration, flushing fluid temperature and flow rate, as well as the pipeline configuration and supporting facilities. These data were subsequently analyzed to identify changes in system performance and evaluate their compliance with the intended operational targets. Available supporting data were then utilized to strengthen the interpretation of the performance improvement mechanisms, such as indications of reduced flow resistance associated with the removal or reduction of wax deposits, without developing a new model or conducting a new simulation. Based on this analysis, the study aims to identify the key parameters influencing the effectiveness of hot water flushing and to formulate technical recommendations to improve the effectiveness, efficiency, and practical applicability of subsequent flushing operations.

This modeling approach is subsequently integrated into various multiphase flow simulation platforms, such as OLGA, to evaluate the effects of wax deposition on flow characteristics in subsea and submarine pipelines, as well as to analyze the sensitivity of key factors influencing the growth rate of the wax layer (Donepudi & Kamerkar 2024).

OLGA simulations were employed to evaluate the hydraulic response of the pipeline under existing conditions and selected flushing flow-rate scenarios using the total liquid volume flow (QLT), liquid superficial velocity (USLT), pressure (PT), fluid temperature, and flow regime as the primary evaluation parameters. This study does not include detailed modeling of wax formation mechanisms, calculation of wax deposit thickness, or transient simulation of wax deposition growth. The main stages in the research include: (1) Basic theory, (2) Data collection, (3) Hypothesis, (4) Research, (5) Screening, (6) Modeling calculation, (7) Results, and (8) Report preparation. Research flow diagram (Figure 1).

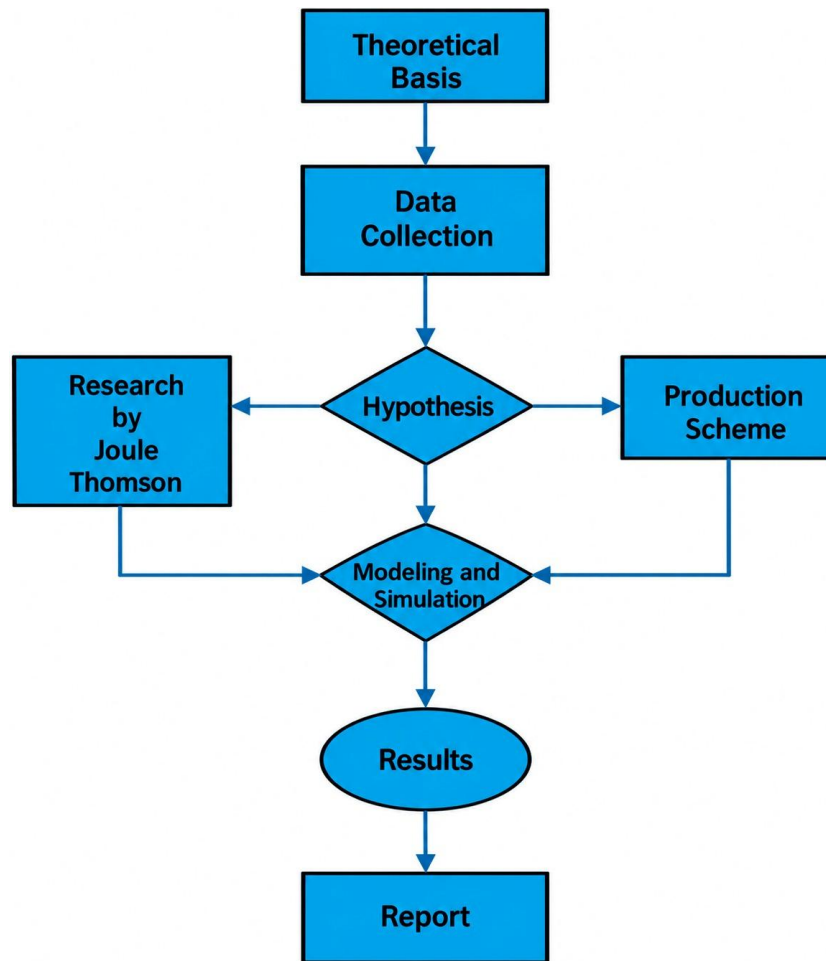


Figure 1.
Research flow diagram.

2.1 Research variables

This subsection describes the variables used in the research, both as inputs (predictors) and outputs (responses) in the modeling. At a temperature of 51°C, which is above the pour point of the crude oil, the oil can be assumed to retain sufficient flowability under the given operating conditions. Input variables (predictors):

- Transfer Pump Pressure (psi)
- Oil flow rate (Bopd)
- Crude temperature
- Fluid density
- Pour pointAmbient temperature
- Crude oil classification

Output variables (responses):

- Temperature minimum operating
- Rate minimum operating

Methodology is designed as an integrated workflow to identifying wax deposition mechanism to improve well production. The initial operating conditions of the pipeline and the characteristics of the produced fluids that contribute to wax deposition potential were first evaluated. The effectiveness of hot water boiwas assessed based on changes in pressure drop, liquid velocity, and production flow rate, which were selected as the primary performance indicators.

This subsection describes the methods used to obtain research data, both through experiments and literature study. Data was collected through two approaches:

- Experiment:
Crude oil sampling was carried out directly with a witness present, and this sample was used for crude assay analysis. Fluid data was obtained from well testing activities.
- Literature Study and Public Database:
Historical data and paraffinic concepts were obtained from reputable scientific journals and chemical databases.

The data was incorporated into the Joule-Thomson equation and simulated using Olga Modeling.

3. Result and discussion

3.1 Data analysis

This subsection explains the procedures used to process and analyze the data that has been collected, as well as the algorithm used to build the predictive model.

The analysis was conducted using a quantitative and evaluative approach based on a comparison of operating conditions before and after the implementation of hot water flushing, as well as the interpretation of available technical data and previously established simulation/calculation results. The analytical procedures consisted of the following steps:

3.1.1 Pipeline system performance evaluation

The evaluation was conducted by comparing pipeline operating data before and after hot water flushing to assess changes in system performance. The primary parameters analyzed included inlet and outlet pressure, pressure drop (ΔP), fluid flow rate, and liquid velocity, which were used as indicators of reduced flow resistance resulting from wax deposition (Chala et al., 2018).

3.1.2 Interpretation of supporting technical data

Supporting technical data, including previously developed flow assurance simulation results or internal calculations, were re-evaluated to understand the effects of increased flow rate and temperature on pressure distribution, fluid residence time, and the potential removal of wax deposits. This interpretation was performed without developing a new simulation model.

3.1.3 Identification of critical flushing parameters

The analysis was conducted to identify the key parameters affecting the effectiveness of hot water flushing, including flushing-water temperature, flushing flow rate, flushing duration, and the initial operating conditions of the pipeline. The assessment focused on the relationship between these parameters and changes in pipeline performance.

3.1.4 Correlation of actual operating conditions with planning/simulation data

Actual field conditions were qualitatively correlated with the assumptions and targets established during the planning or simulation stages to assess the degree of consistency between idealized conditions and actual operating conditions. This analysis aimed to identify the root causes when the flushing results did not achieve the expected targets.

3.1.5 Formulation of technical recommendations

Based on the performance evaluation and data interpretation, practical technical recommendations were formulated to improve the effectiveness of hot water flushing operations. The recommendations focused on optimizing operating parameters and implementation procedures without developing a new pipeline system design or conducting additional simulations:

- The analysis method in this research uses a quantitative approach through numerical simulation with the OLGA software to analyze the phenomenon of paraffin wax deposition in the production piping system. The analysis was carried out by evaluating the temperature, pressure, and flow-rate profiles, and the initial location where wax formation begins.
- The statistical tools used in this research are descriptive analysis and multiple linear regression analysis, complemented by a t-test (Simultaneous Hypothesis Test) and an F-test (Partial Hypothesis Test) to determine the effect of temperature and flow rate on the formation and deposition of paraffin wax in the production piping system based on the OLGA simulation results.

This subsection explains how the validity and reliability of the calculations and the predictive model developed were tested so that the research results can be trusted and relied upon. The evaluation was conducted based on the main hydraulic and operational parameters, including flow rate, liquid velocity, pressure profile, fluid temperature, water cut, pipe diameter, pipeline length, elevation profile, and the operating pressure limit relative to the Maximum Allowable Operating Pressure (MAOP). Other parameters, such as detailed wax composition, comprehensive fluid rheological properties, thermal characteristics of the deposits, and oil–water emulsion phenomena, were not analyzed in depth in this study. The validity of the model was tested through:

- Calculation Validity: Calculating and observing the trend of temperature drop against distance.
- Predictive Validity: Measuring the model's ability to predict the pipe and transfer system in the simulation.
- Content Validity: Obtained through the selection of variables based on theory and literature.

Model reliability was tested through:

- Replication and cross-validation: To check the consistency of the model results across different data subsets.
- Model parameter stability: Assessed based on the fluctuation of prediction results against minor input variations.

With this approach, the resulting predictive model is expected to be not only statistically accurate but also reliable and practically usable for system evaluation and design. Explains the methodological approach used to answer the research questions and achieve the established objectives. This research is quantitative in nature, using a process-data-based predictive modeling approach carried out through the collection and processing of fluid physical property data and production behavior characteristics. The following is information on the production scheme that will be used: In this field's production scheme, fluid from the wells flows to the early production facility (EPF); after fluid processing, the crude oil is held in a temporary tank on land.

Wax deposition in offshore pipeline systems is a common flow assurance challenge that can lead to increased pressure drop, reduced flow capacity, and potential production losses in offshore oil and gas facilities. This condition generally occurs when the fluid temperature falls below the Wax Appearance Temperature (WAT), causing paraffin components in the crude oil to precipitate and deposit on the inner pipe wall, thereby reducing the effective flow area, particularly under low-flow-rate conditions and high fluid viscosity. Various wax mitigation strategies have been implemented, including the use of inhibitors, pigging, and thermal treatment methods such as hot water flushing, which are intended to soften and remove wax deposits and consequently restore the hydraulic performance of the pipeline (Elkatory et al., 2022).

To keep the oil temperature within the liquid phase, water heating is used, drawing from fresh water processed through reverse osmosis for the boiler, which is distributed through coils inside the temporary tank. The crude oil transfer process uses a 6-inch pipe over a distance of 6 km to the Floating Storage Offloading unit.

Based on the field's operational layout, crude fluid is produced from several active wells and flows to the Early Production Facility (EPF), with the following logistic distance details:

- Well SED-1 to EPF: pipe distance of 1.5 km.
- Well SED-3 to EPF: pipe distance of 4.5 km.
- Well SED-4 to EPF: pipe distance of 4.5 km.
- Carbon steel pipe sleep on ground
- Mineral wool with stainless steel cladding

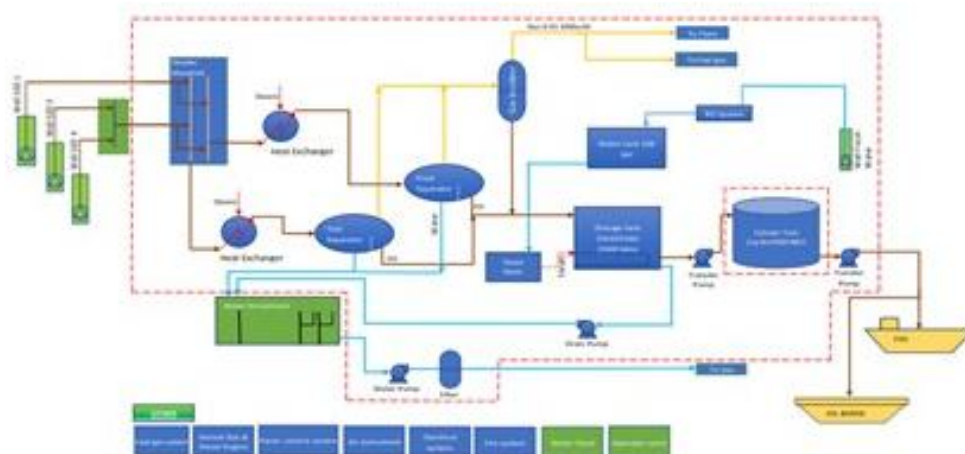


Figure 2.
Research flow diagram

Multiphase Separation involves separating the fluid into several phases (oil, gas, and water) using separation equipment such as separators. Light Treatment includes further treatment to improve crude oil quality, remove contaminants, and carry out stabilization. Storage and Export (Downstream) includes storing the oil product in tanks and preparing it for export, including transferring it via a piping system to the final storage facility or floating storage.

The Utility support system provides needs such as cooling water, steam, electricity, and cooling to keep separation and processing operations running. Gas, liquid, and water flow through pipes from the wells to the processing units and finally to the storage facility.

The support/utility system continuously provides essential needs such as water, steam, electricity, and cooling to keep separation and processing operations running smoothly. Gas, oil, and water flow through pipes from the wells, through processing units, to the storage facility. Key equipment involved includes headers, separators, pumps, storage tanks, and transfer systems, supported by water treatment facilities, instrumentation, and automatic control to ensure operations remain controlled and efficient. This flow underscores the importance of balanced flow between stages to avoid bottlenecks, as well as utility readiness to maintain process stability. Overall, the EPF is designed to carry fluid from the wells to the floating storage facility in a controlled manner through a series of processing, storage, and transfer stages supported by reliable control and utility systems (Figure 3).



Figure 3.
Reverse osmosis water treatment as boiler inlet.

Reverse Osmosis (RO) is a separation process that uses a semipermeable membrane with the aid of high pressure to produce high-quality water by removing dissolved salts, particles, and contaminants from raw water.

The limited effectiveness of Pour Point Depressant (PPD) in heavy high-waxy crude oil can be attributed to several factors, including the high wax content, high base-oil viscosity, and the compatibility between the chemical structure of the PPD and the wax components present in the crude oil. PPD does not remove wax from the crude oil; rather, it primarily modifies the morphology and growth of wax crystals, thereby reducing the tendency of the crystals to form a rigid three-dimensional network that can significantly restrict fluid flow.

In heavy crude oil with a high wax content, the quantity of wax available for crystallization is relatively large. Consequently, even when PPD modifies the morphology of the wax crystals, the remaining wax crystals may still interact and form a continuous structure within the oil. This condition can limit the improvement in flowability, particularly at temperatures approaching or below the Wax Appearance Temperature (WAT).

Furthermore, the inherently high viscosity of heavy crude oil can remain a significant source of flow resistance. The application of PPD may reduce the strength of the wax crystal network, but it does not substantially reduce the intrinsic viscosity of the base oil. Therefore, a reduction in pour point does not necessarily correspond to a proportional improvement in pipeline flowability or hydraulic performance. The effectiveness of PPD is also strongly dependent on its compatibility with the molecular characteristics of the crude oil and its wax composition. The molecular structure, carbon-number distribution, and concentration of paraffinic components can influence the interaction between the PPD molecules and the wax crystals. Consequently, a PPD formulation that is effective for one type of crude oil may exhibit limited effectiveness when applied to another crude oil with different wax characteristics.

It is also important to distinguish between pour point reduction and wax deposition control. A decrease in pour point indicates that the treated crude oil can retain its apparent flowability at a lower temperature under the specified test conditions. However, this does not necessarily indicate that wax crystallization or deposition has been eliminated. If the operating temperature remains below the WAT, wax crystals may still precipitate and potentially deposit on the inner wall of the pipeline.

Therefore, for heavy high-waxy crude oil, the effectiveness of PPD should not be evaluated solely based on the reduction in pour point. Other parameters, such as WAT, viscosity, wax content, pressure drop, liquid velocity, and the actual extent of wax deposition, should also be considered. In cases where significant wax deposits have already accumulated inside the pipeline, thermal treatment methods such as hot water flushing may provide a more direct approach because the increased temperature can soften and mobilize the existing wax deposits, thereby helping to restore the effective flow area and hydraulic performance of the pipeline (Yao et al., 2022).

- The dual fuel boiler is designed to use two types of fuel, such as natural gas and diesel oil, providing operational flexibility and increasing the reliability of the steam generation system.
- Main Components
- Dual fuel burner
- Gas supply system
- Liquid fuel supply system
- Control and instrumentation system
- Safety interlock system

All wells produced from the Sepanjang Field are processed at the EPF to treat the oil. The crude oil is held in the EPF oil tank, which has an operational capacity of 5,000 STB. Once a sufficient volume for loading is reached, the crude oil is pumped through a 6-inch pipeline over a distance of 6 km sleep on ground this pipe, then stored in OB. Ramba Pratama, which has a (gross) loading capacity of 3,797 M3 or 23,885 STB across 12 tanks, and TST MT Jade, with a (gross) loading capacity of 8,362 m3 or 52,595 STB across 14 tanks. For crude oil transactions after lifting has been carried out, a Liquid Custody Metering System is required as a means of conducting the custody meter transaction of crude oil from seller to buyer.

The Crude Oil Loading Point for the delivery of crude oil from TST MT Jade to the Tanker Buyer vessel at the Sepanjang Terminal is located at the final flange of the outlet flexible hose on the PD Meter, and represents the point at which operational responsibility is transferred to the buyer.



Figure 4.
Dual fuel water boiler.



Figure 5.
Floating storage tank.

Temperature drop at a distance of 800 meters, to a temperature below the pour point, will result in a potential plug in the pipe. A heating system is therefore needed to maintain temperature up to the delivery point during oil transfer.

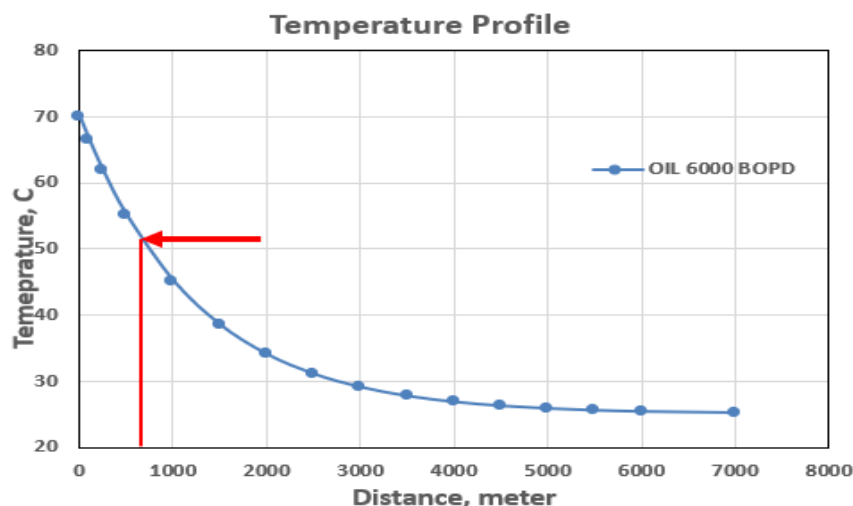


Figure 6.
Temperature vs distance.

Based on the calculation results using the Joule-Thomson equation, the fluid temperature profile along the pipeline route from the production facility to the Floating Storage and Offloading (FSO) unit was obtained, as shown in Figure 6. The graph shows the change in oil temperature at a flow rate of 6,000 BOPD with respect to pipeline distance. The calculation results show that the fluid temperature decreases significantly at the beginning of the pipeline segment. The oil temperature, which was initially around 70°C at the production facility outlet, gradually decreases due to heat transfer from the fluid to the surrounding environment through the pipe wall. The rate of temperature decrease is relatively high at the beginning of the route because the temperature difference between the fluid and the environment is still fairly large, resulting in a higher rate of heat loss. Maintenance of this temperature above pour point temperature justifies crude oil free wax deposition.

At a distance of around 800 meters, the fluid temperature has reached around 50°C, which is below the crude oil's pour point value. This condition indicates that the oil begins to lose its ability to flow optimally due to increasing viscosity and the formation of paraffin crystals. If this condition is allowed to continue during operations, the paraffin crystals will keep growing and form a deposit layer (wax deposition) on the inner wall of the pipe.

On the other review studies concerning the transportation of waxy crude oil through offshore pipeline systems have emphasized that maintaining flow reliability requires an integrated approach encompassing thermal management, hydraulic considerations, and operational design. Such an approach includes maintaining appropriate operating temperatures, controlling flow rates, and implementing periodic pipeline cleaning strategies to minimize excessive wax accumulation and maintain the hydraulic performance of the system (Bell et al., 2021).

In field operations, one of the practical applications of thermal management is high-temperature fluid flushing, which can be implemented during both the pre-commissioning stage and normal operation as a corrective measure. This method is intended to remove accumulated deposits that may restrict the effective flow area and consequently impair pipeline hydraulic performance. The effectiveness of this approach is strongly influenced by the flushing-fluid temperature, flow rate, and duration, which must be appropriately controlled according to the operating conditions and characteristics of the deposited material. The accumulation of this deposit has the potential to narrow the pipe's effective diameter, increase pressure drop, reduce flow capacity, and eventually form a wax plug that can impede or even stop the oil transfer process (Ratnakar et al., 2025).

After a distance of about 3,000 meters, the rate of temperature decrease begins to slow, approaching a lower steady-state condition, with the fluid temperature in the range of 25–27°C until it reaches the delivery point at the FSO. This indicates that the fluid temperature has approached the ambient temperature, so the rate of heat

transfer becomes smaller. Based on this analysis, it can be concluded that the critical distance at which the temperature drop becomes significant is around 800 meters, i.e., when the fluid temperature falls below the pour point value. Therefore, a flow assurance method in the form of a heating system is needed, one capable of keeping the fluid temperature above the Wax Appearance Temperature (WAT) and the pour point throughout the oil transfer process.

The effectiveness of PPD is also strongly dependent on its compatibility with the molecular characteristics of the crude oil and its wax composition. The molecular structure, carbon-number distribution, and concentration of paraffinic components can influence the interaction between the PPD molecules and the wax crystals. Consequently, a PPD formulation that is effective for one type of crude oil may exhibit limited effectiveness when applied to another crude oil with different wax characteristics.

It is also important to distinguish between pour point reduction and wax deposition control. A decrease in pour point indicates that the treated crude oil can retain its apparent flowability at a lower temperature under the specified test conditions. However, this does not necessarily indicate that wax crystallization or deposition has been eliminated. If the operating temperature remains below the WAT, wax crystals may still precipitate and potentially deposit on the inner wall of the pipeline.

Therefore, for heavy high-waxy crude oil, the effectiveness of PPD should not be evaluated solely based on the reduction in pour point. Other parameters, such as WAT, viscosity, wax content, pressure drop, liquid velocity, and the actual extent of wax deposition, should also be considered. In cases where significant wax deposits have already accumulated inside the pipeline, thermal treatment methods such as hot water flushing may provide a more direct approach because the increased temperature can soften and mobilize the existing wax deposits, thereby helping to restore the effective flow area and hydraulic performance of the pipeline.

One method that can be applied is hot water injection, which functions to raise the fluid temperature so that wax crystal formation can be prevented. By keeping the fluid temperature above this critical threshold, the risk of wax deposit formation can be minimized, so that production continuity, oil transportation system efficiency, and pipeline operation reliability can be maintained (Jiang et al., 2020).

Crude oil with a high paraffin content flows inside the pipe. When the fluid temperature drops below the Wax Appearance Temperature (WAT), paraffin begins to crystallize and adhere to the pipe wall. As wax crystals continue to accumulate (agglomeration):

- The pipe's effective diameter narrows.
- The flow rate decreases.
- Pressure drop increases.
- The risk of plugging increases.

The (Figure 7) The process of wax formation and its reaction to hot water boiler shows that: Hot water at a temperature of around 90°C is injected into the pipe. Raises temperature of the oil and the pipe wall. The wax that was previously solid begins to melt (melting) and dissolve back into the oil, partly forming a slurry (a mixture of oil and liquid wax).

The Wax Disappearance Temperature (WDT) is defined as the temperature at which previously formed wax crystals or deposits begin to disappear, dissolve, or become sufficiently mobilized as the crude oil is heated. WDT is an important parameter in flow assurance because it provides an indication of the thermal condition required to reduce or eliminate wax that has previously precipitated from the crude oil (Brown & Dobbs 1998).

WDT is closely related to the Wax Appearance Temperature (WAT), but the two parameters represent different thermal conditions. WAT refers to the temperature at which wax crystals initially begin to precipitate from the crude oil during cooling, whereas WDT represents the temperature at which the previously formed wax phase begins to disappear during heating. Therefore, WDT is particularly relevant to thermal remediation and pipeline cleaning operations involving wax deposits.

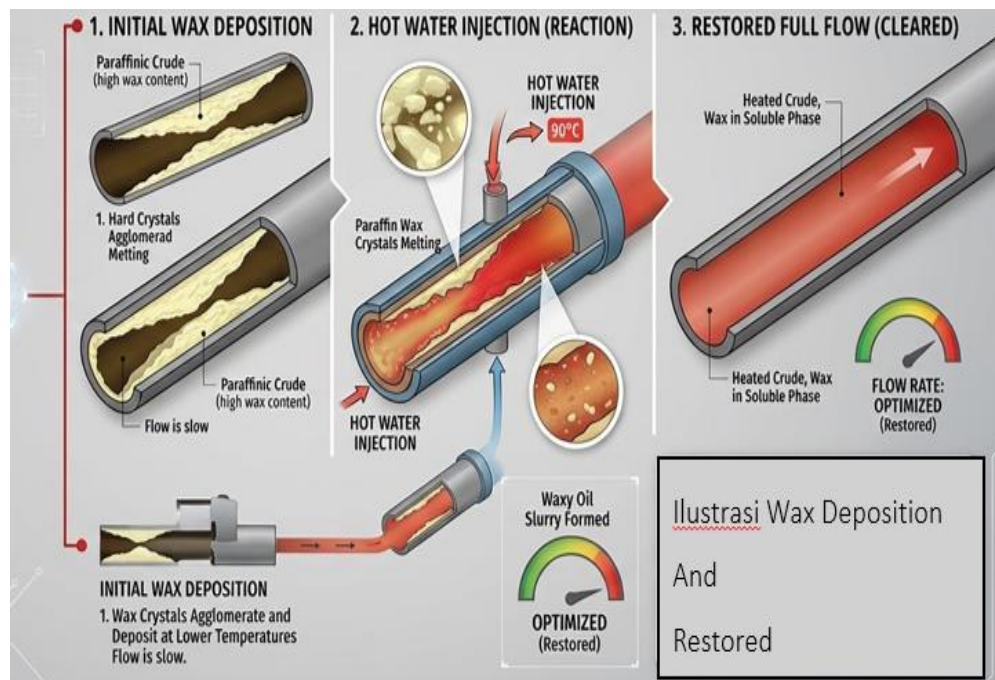


Figure 7.
The process of wax formation and its reaction to hot water injection.

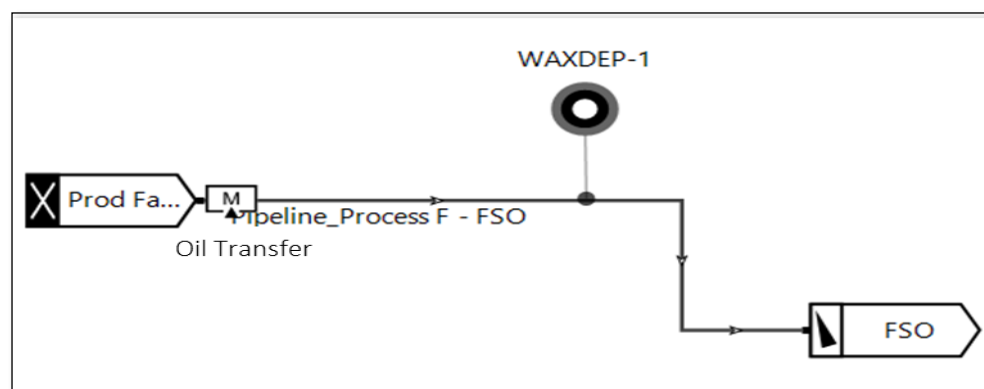


Figure 8.
Oil transfer scheme.

In the context of hot water flushing, the flushing fluid transfers heat to the pipeline wall and subsequently to the accumulated wax layer. As the temperature of the wax deposit increases, its structure may weaken and the deposit may become softened, partially dissolved, dispersed, or removed by the shear force generated by the flowing hot water. Accordingly, the flushing temperature should be sufficiently high to provide effective heat transfer and promote wax removal (Jing et al., 2025).

The purpose of this stage is to remove the wax deposit, reopen the flow area inside the pipe, and reduce operating pressure. A simulation model of the oil transfer system from the Early Production Facility to the Floating Storage and Offloading (FSO) unit was built using the OLGA software. This model is used to analyze multiphase flow behavior and evaluate the potential for wax deposition during the crude oil transportation process through the pipe.

On the upstream side, the Early Production Facility functions as the flow source, injecting production fluid into the piping system. The fluid transported is crude oil with specific characteristics based on the PVT data determined during the modeling stage. The fluid then flows through Pipeline_Process F – FSO, which represents the oil transfer pipe route from the production facility to the FSO. Along the pipe route, a WAXDEP-1 component is installed, a wax deposition monitoring and calculation module provided by OLGA. This module is used to calculate the wax deposit formation rate, the thickness of the wax layer on the pipe wall, and the change in the pipe's effective diameter due to the accumulation of paraffin deposits during operation. These calculations are performed dynamically based on changes in temperature, pressure, fluid composition, and the thermodynamic characteristics of the crude oil. The following is the fluid composition (Table 3).

Table 3.
Fluid composition

No	Component	Wellstream Mole %
1	H ₂ S	0.00
2	CO ₂	4.35
3	N ₂	0.93
4	C ₁	22.68
5	C ₂	2.4
6	C ₃	2.51
7	iC ₄	0.85
8	nC ₄	1.31
9	iC ₅	0.7
10	nC ₅	1.09
11	C ₆	0.67
12	C ₇₊	62.51
13	Total	100

The placement of the WAXDEP-1 module in the pipe segment is intended to evaluate the critical conditions under which wax deposition occurs along the oil transfer route. The information generated by this module forms the basis for analyzing the severity of oil flow problems, particularly those related to a decrease in fluid temperature below the Wax Appearance Temperature (WAT). If the fluid temperature is lower than the WAT, paraffin components begin to crystallize and deposit on the inner surface of the pipe, potentially increasing pressure loss (pressure drop), reducing the flow cross-sectional area, and decreasing the fluid transport capacity.

On the downstream side, the FSO (Floating Storage and Offloading) unit acts as the output boundary (sink) of the simulation system, representing the receiving and storage facility for produced oil before further transport takes place. Thus, this simulation model dynamically represents the entire oil transfer process from the production facility to the FSO, allowing for analysis of pressure distribution, temperature, flow rate, and the tendency for wax formation along the pipe route. This simulation model serves as the basis for evaluating the performance of the piping system and assessing the effectiveness of various flow assurance mitigation scenarios, such as hot water injection, in reducing the rate of wax deposition and restoring the oil flow capacity of the transfer system.

Fluid analysis was carried out using samples originating from Sepanjang Island (native data). This native data comes from DST-2C test data. The fluid composition and PVT laboratory results are shown in (Figure 9) Based on the test data, the initial condition of SED at DST-2C is at an initial pressure of 2,217 psi. The recorded temperature is 235°F, with the bubble point pressure at 906 psi show (Table 4) PVT Data.

Table 4.
PVT data

No	PVT Parameter	Well (SED)
1	Initial Pressure, psi	2217
2	Temperature, °F	235
3	Bubble Point (Pb), psi	906
4	Solution GOR at Pb, scf/stb	144
5	Oil Viscosity @ Pb, cp	4.89
6	Oil Density @ Pb, gm/cc	0.8054

The DST-2C data, together with the CCE and DLE test data, were regressed using the PVTP software from IPM version 7.5.600 using the Peng Robinson equation. This regression method was carried out by regressing the pseudo component at C7+ for its critical pressure, critical temperature, and acentric factor. Based on the phase envelope construction shown in (Figure 9) phase envelope, the regressed bubble point pressure obtained is 908 psig at a temperature of 235°F. The viscosity in this PVT data was regressed using the Lohrenz Bray Clark approach. The matching results are shown in (Figure 9) Phase envelope, where the regression results already match the lab data. The difference between the lab data and the regression results, or Absolute Average Error (AAE), is below 5% overall, so this data will be exported for use in dynamic modeling of the SED field.

A comprehensive laboratory analysis of the crude oil to determine its physical and chemical characteristics, in order to determine its economic value, quality, and refinery processing strategy; determine crude oil quality; predict refinery product yield; determine refinery configuration and operating conditions; assist with crude pricing and marketing; and identify potential operational issues (corrosion, fouling, high sulfur, etc.). Main Parameters Analyzed:

- Physical Properties: 1). API Gravity; 2).Density; 3).Viscosity; 4).Pour Point; 5).Color
- Chemical Properties: 1).Sulfur content (sweet vs sour crude); 2).Total Acid Number (TAN); 3).Nitrogen content; 4).Metals (Ni, V, Fe); 5).Salt & water content
- Distillation Analysis: 1).True Boiling Point (TBP) distillation; 2).ASTM distillation; 3).Resulting fractions: Naphtha, Kerosene, Gas Oil, Residue
- Yield & Product Quality: 1).Percentage of each fraction; b).Product quality (naphtha RON, diesel sulfur, etc.)

Crude Assay Summary:

- API Gravity: 33.6° API
- Specific Gravity at 60/60° F: 0.8573
- Pour Point: > 51°C
- Sulfur Content: 0.096 %wt
- Asphaltene Content: 0.076 %wt
- Wax Content: 19.75 %wt
- Classified: Paraffinic – Paraffinic

Crude oil with an API gravity of 33.6° across the Sepanjang range is classified as “Paraffinic–Paraffinic” according to the U.S. Bureau of Mines classification.

- The gasoline fraction has a low yield and low octane number.
- The naphtha fraction has a low yield and low aromatic content.
- The kerosine fraction has a medium yield and a high smoke point.
- The gasoil fraction has a medium yield and a high cetane index.

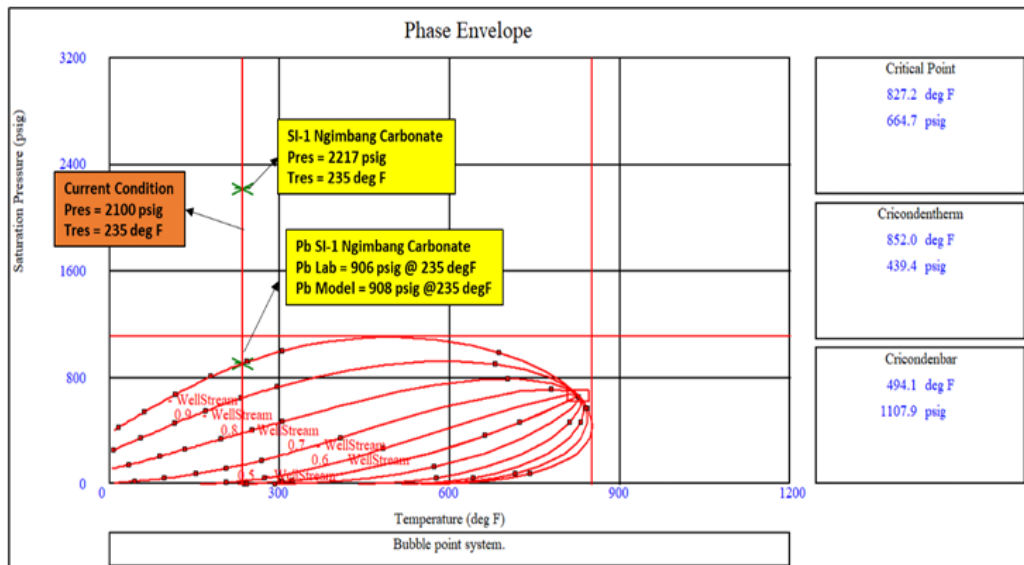


Figure 9.
Phase envelope.

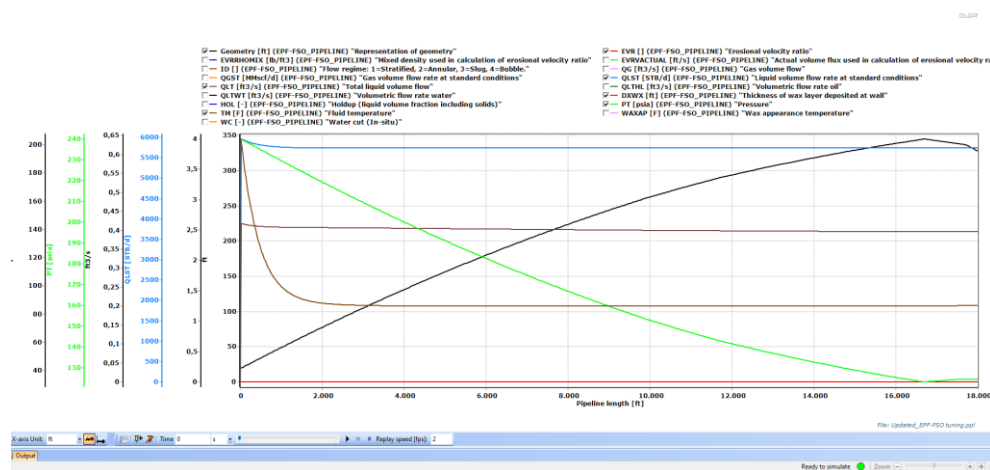


Figure 10.

Based on the steady-state simulation results obtained using OLGA 2023.1.0 for the EPF-FSO pipeline with a total length of 18,000 ft.

4. Conclusion

Simulation results using the OLGA software for the oil transfer piping system from the Process Facility to the FSO. The graph shows (figure 10) changes in several important parameters against pipeline length, namely:

- Geometry,
- QLST (Liquid Flow Rate at Standard Conditions).
- DXWX (Wax Layer Thickness).
- PT (Pressure).
- TM (Fluid Temperature).
- WAT (Wax Appearance Temperature)

The operational parameter profiles are described as follows:

4.1 Geometry profile (geometry [ft])

The black line represents the pipeline elevation profile along its total length. The pipeline geometry exhibits a continuous positive slope from the inlet at 0 ft to a maximum elevation at approximately 16,500 ft. Beyond this point, the elevation decreases slightly toward the pipeline outlet at 18,000 ft. This profile indicates that the pipeline predominantly follows an uphill configuration throughout most of its length.

4.2 Fluid temperature profile (TM [°F])

The brown line illustrates the fluid temperature distribution along the pipeline. The inlet temperature is approximately 240°F. A significant and rapid temperature decline occurs within the first 2,000 ft, decreasing from approximately 240°F to 110°F. Beyond 4,000 ft, the fluid temperature becomes relatively stable at approximately 105°F until the pipeline outlet. The sharp temperature reduction in the initial section indicates substantial heat loss from the fluid to the surrounding environment.

4.3 Pressure profile (PT [psia])

The red line represents the pressure profile along the pipeline. The inlet pressure of approximately 340 psia decreases rapidly within the first 500 ft to about 325 psia. Thereafter, the pressure remains relatively constant until approximately 15,000 ft. Between 15,000 ft and 16,500 ft, the pressure increases to a peak value of approximately 350 psia, corresponding to the maximum elevation observed in the pipeline geometry profile. Subsequently, the pressure decreases slightly toward the pipeline outlet.

4.4 Wax Deposition Thickness (DXWX [ft])

The blue line shows the thickness of the wax layer deposited on the inner wall of the pipeline. The maximum wax thickness occurs near the inlet and decreases exponentially within the first 2,000 ft. After approximately 4,000 ft, the wax thickness approaches zero and remains nearly constant until the outlet. These results indicate that significant wax deposition is concentrated primarily in the upstream section of the pipeline.

4.5 Wax Appearance Temperature (°F)

The magenta line represents the Wax Appearance Temperature (WAT), which corresponds to the temperature at which wax crystals begin to form. The WAT remains relatively constant throughout the pipeline at approximately 5°F, indicating that this thermodynamic property is essentially unchanged along the pipeline under the simulated operating conditions.

4.6 Liquid Flow Rate (QLST [STB/d])

The red line represents the liquid flow rate along the pipeline. The QLST remains relatively stable throughout the system, decreasing only slightly from approximately 6,000 STB/d at the inlet to around 5,800 STB/d at the outlet located at 18,000 ft. This gradual decline in liquid flow rate may indicate liquid accumulation, phase redistribution, or minor fluid-property changes occurring along the pipeline under steady-state operating conditions.

4.7 Recommendation

Alternative development scenarios may be investigated by evaluating the transfer of crude oil mixed with water to assess its influence on flow assurance performance and wax deposition characteristic. Additional development scenarios may be explored by blending the crude oil with pour point depressants (PPDs) or other flow assurance chemicals to evaluate their effectiveness in mitigating wax deposition and improving pipeline operability. At the field scale, further studies may investigate blending the produced crude oil with lighter crude oil from nearby fields, where operationally feasible, to facilitate lifting operations and improve the flow characteristics of the transported crude.

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6. Declarations

6.1 Author contributions

Tio Rizky: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Formal analysis, Investigation, Visualization. Muh Kurniawan: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Investigation, Validation, Data Curation and supervision. Silvy Dewi R: were involved in conceptualization, methodology development, supervision, and reviewed and edited the manuscript, Formal analysis, Resources, Software, Visualization.

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6.3 Competing interest

The authors declare that there are no competing financial, professional, or personal interests that have influenced, or could reasonably be perceived to have influenced, the work reported in this manuscript. The authors further confirm that they have no affiliations or involvement with any organization or entity that could give rise to a conflict of interest concerning the subject matter discussed in this article.

6.4 The use of AI-assisted technologies

During the preparation of this manuscript, the authors utilized Open AI's ChatGPT exclusively as an AI-assisted language support tool to enhance grammar, language quality, clarity, and readability. The generated text was thoroughly reviewed, critically evaluated, and substantially revised by the authors to ensure its accuracy, consistency, and adherence to accepted scientific and ethical standards. The AI tool was not used for data generation, data analysis, interpretation of results, or scientific decision-making. The authors retain full responsibility for the originality, accuracy, and integrity of all content presented in this manuscript.

7. Glossary of terms and symbols

Terms & Symbol	Definition	Unit
U	heat transferred per area (panas yang berpindah per luas area)	W/m ²
K	overall heat transfer coefficient (koefisien perpindahan panas keseluruhan)	
A	heat transfer area (luas area perpindahan panas)	m ²
ΔT_{LMTD}	logarithmic mean temperatur difference (perbedaan temperatur rata-rata logaritmik)	K
q	heat transferred (panas yang berpindah)	W
m	mass flow rate inside pipeline (laju alir massa di dalam pipa)	kg/s
C _p	heat capacity of fluid mixture (kapasitas panas campuran fluida)	J/kg
T ₁	pipeline inlet fluid (upstream) temperature (temperatur fluida masuk pipa/hulu)	K
T ₂	pipeline outlet fluid (downstream) temperature (temperatur fluida keluar pipa/hilir)	K
L	length of pipeline segment or a whole pipeline (panjang segmen pipa atau pipa keseluruhan)	m
d	pipeline internal diameter (diameter internal pipa)	m

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