



The Effect of Heat Tracing Installation for Wax Prevention on Onshore Buried Swampy Pipelines

Samuel Bagas Wahyu Santoso*, Andy Noorsaman Sommeng, Cindy Dianita

Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, 16421

*E-mail: samuel.bagas@ui.ac.id

Article History

Received: 9 March 2024; Received in Revision: 30 April 2024; Accepted: 8 May 2024

Abstract

Transporting crude oil using pipelines is a widely adopted method globally. In one segment owned by PT. XYZ, especially in swampy areas, the fluid temperature tends to drop below the wax appearance temperature (WAT) during oil transportation. This is due to the relatively low temperature in swamp areas caused by heat loss to the environment. The solubility of paraffin in crude oil drastically decreases as fluid temperature drops, causing wax molecules to precipitate and deposit on the cold pipe walls. PT. XYZ employs chemical treatment by adding a pour point depressant (PPD) to lower the pour point temperature (PPT). However, PPD is effective only at certain temperatures, necessitating a study for alternative treatments. Another method involves installing heaters on the pipeline to reduce the viscosity of transported crude oil and enhance its flowability, either through direct heating or heat tracing using insulation with low thermal conductivity. Therefore, in PT. XYZ's case, an analysis is required to identify locations where fluid temperature decreases occur to ensure precise heater installation. Various software tools, including OLGA, have been developed to predict and describe wax deposition phenomena and temperature decreases along the pipeline. OLGA software can simulate locations of fluid temperature decreases in the pipeline, estimate heat loss along the pipeline, and simulate heat tracing technologies to prevent wax deposition. Simulation results indicate that wax deposition can be prevented by installing skin effect heat tracing with a heating power of 15 W/m and insulated with 2-inch aerogel, maintaining the oil temperature downstream at 157.34°F, well above the desired 115°F threshold.

Keywords: flow assurance, heat tracing, insulation, OLGA simulation, wax deposition

1. Introduction

For over seven decades, crude oil has played a crucial role in the global economy. Its function as a fuel source for industrial sectors, power generation, and transportation makes it a key element in supporting a country's economic growth. Furthermore, the demand for crude oil continues to increase annually. According to statistics, in 2023, the consumption rate of crude oil reached 102 million barrels per day. Organization of the Petroleum Exporting Countries (OPEC) predicts that the demand for crude oil will reach 104.3 million barrels per day in 2024, marking a growth of approximately 2.3 million barrels compared to the previous year (Organization of the Petroleum Exporting Countries, 2023).

The oil and gas industry in Indonesia continues to be one of the leading sectors driving national economic growth. The Central Sumatera Basin (CSB) is recognized as a basin with abundant crude oil production, encompassing both light and medium crude oil

types (Rahmat & Wiranatanegara, 2021). This particular basin is referred to as the Rokan Block. The Rokan Block is located in the Riau Province, specifically in the Bengkalis Regency, Siak Regency, and Rokan Hilir Regency. This block is one of Indonesia's major contributors to oil and gas production, accounting for approximately 25% of the country's total oil production. Its production level reached an average of 160 thousand barrels of oil per day (BOPD) during the period from September to December 2021 (Felandry et al., 2022).

PT. XYZ is a company that focuses on the midstream and downstream sectors, with one of its businesses being the transportation of crude oil through a pipeline network. The pipeline network owned by the company spans approximately 290 km for Sumatera Light Crude (SLC) and around 80 km for Duri Crude (Heavy Oil / HO), with all pipeline networks located in the Rokan Working Area (WK Rokan). Pipelines are a common method of transporting crude oil worldwide. To mitigate risks during the transportation process, some

pipelines are constructed underground (buried) (Yuan et al., 2023).

Segment X, which runs from Gathering Station X (GS X) to Tie-in X, is currently addressing issues such as congealing and pig stuck. The pipeline is buried underground, and approximately 80% of it is located in swampy environments. This is due to the relatively low temperatures in swampy areas, which result in heat loss to the environment during the production and transportation processes. (Alnaimat & Ziauddin, 2020). The solubility of paraffin in crude oil will decrease dramatically as the fluid temperature drops. Wax molecules begin to precipitate and deposit on the cold pipe walls (Venkatesan et al., 2005). Without adequate thermal insulation, crude oil pipelines buried in swamps will experience heat loss. Essentially, the pipeline undergoes heat transfer with its surrounding environment, which may have a lower temperature. This heat loss can lead to a decrease in the temperature of the crude oil inside the pipeline (Yuan et al., 2023).

Other issues, such as wax deposition in oil pipeline infrastructure, can exacerbate the temperature decrease and affect the smoothness of production in those fields. Wax deposition, or wax buildup, is a significant problem in the oil industry and has substantial economic impacts. According to a study, the impact of wax deposition in energy production, particularly in the oil and gas industry, ranges in value from 14.736 billion to 330.585 billion USD per year, with an expected value of 47.620 billion USD per year. The two main losses that significantly contribute to this value are the reduction in flow rates due to blockages and production losses due to downtime (Sousa et al., 2022).

Currently, PT. XYZ employs chemical treatment by adding a pour point depressant (PPD) to lower the pour point temperature (PPT). PPD is only effective in reducing crude oil's pour point temperature to a specific temperature. If the temperature drops below this point, PPD may no longer be effective, and crude oil may experience wax deposition. PPD is an additional chemical that incurs significant costs. One of the main challenges associated with the use of PPD is the cost of procurement and purchasing, which can become a substantial expenditure factor for field operators. Typically, the price of PPD is relatively high, particularly for concentrations that effectively address crude oil freezing issues. Additionally, these costs can escalate with increased oil production volume or greater demand for PPD in the industry. For

instance, reducing the oil pour point temperature to 26°C requires approximately 3000–5000 ppm per day. If estimated, every day, PT. XYZ requires a fee of Rp. 53,662,500–89,437,500, depending on the PPD vendor.

Furthermore, the use of PPD necessitates careful management strategies in its arrangement and procurement. To meet these needs, field operators must estimate the amount of PPD required and make accurate cost projections. This may involve complex budget planning and necessitate significant fund allocations within the operational budget. In terms of procurement costs, field operators must also consider price variations in PPD that may occur due to market fluctuations and supply availability. Changes in PPD prices and availability can pose additional risks to operational budget management, especially in the event of unexpected price hikes or delays in PPD supply delivery.

Using OLGA software, previous research identified wax deposition for offshore oil pipelines in the Charlie-Bravo field with a flow rate of 80,000 BOPD. Wax deposition began to form when the oil reached its WAT point at 31.1 degrees at a distance of 4 km from its total length of 75 km. The total accumulated wax deposition over 82 days was 1 mm, so we recommend pigging at every 82-day interval. However, this study did not discuss its thermal remediation or prevention strategies (Thaher, 2014). Several investigations have been conducted on electric heating technology to prevent wax deposition in pipelines, focusing on the subsea flowline of the North Sea in Norway, where pipelines span lengths of 8 km and 50 km using OLGA software. In previous studies, only a segment of the pipeline was consistently heated, starting from the point where the bulk fluid temperature reaches the WAT. For both the 8 km and 50 km pipelines, the power consumption per meter did not exceed 400 W/m (González et al., 2018). In 2008, during the Mangala Development Pipeline (MDPL) project in India, the skin effect type heat tracing technology combined with insulation installation became a solution to address wax deposition issues. Most of the pipes that are built are placed in dry soil. The crude oil originating from the Barmer-Rajasthan basin contained a wax content of 38% w/w and a pour point temperature between 32–34°C (Hamill et al., 2017).

None of the aforementioned studies have ever successfully reduced wax deposition on oil pipes installed in wet swamp soil. A study is needed to explore alternative treatments.

Therefore, in the case of PT. XYZ, an analysis is needed to identify the locations where fluid temperature decreases occur so that the installation of heat tracing devices can be precisely targeted. Various software tools have been developed to predict and depict wax deposition phenomena, as well as locations of temperature decreases. One such software is OLGA. The OLGA software can be utilized to simulate the processes of wax deposition and temperature reduction as a function of time and location along the pipeline.

2. Methodology

2.1. Crude Oil and Wax

Crude oil is made up of different hydrocarbons, commonly including paraffin wax, aromatic hydrocarbons, resin, asphaltene, and other elements. The wax proportion in crude oil can reach as high as 33% (Rehan et al., 2016).

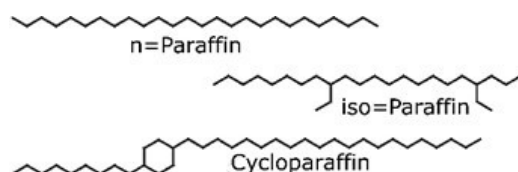


Figure 1. Paraffin wax structure

Wax in crude oil plays a significant role in the oil and gas industry, as it can significantly impact the performance of oil production and transportation. Physically, wax can precipitate and form solid layers inside oil pipelines, known as wax deposition. This process mainly occurs under low temperature and pressure conditions, such as in subsea pipelines or in areas with low ambient temperatures. Wax deposition can cause a decrease in oil flow, increase viscosity, and reduce production and transportation efficiency (Huang et al., 2015). Paraffin wax deposition with high molecular weight is commonly found in solid wax deposits, where the number of carbon atoms ranges from 18 to 75, and its melting point ranges from 40°C to 70°C (Ragunathan et al., 2020). As illustrated in Figure 1, the majority of paraffin wax consists of normal paraffin (80-90%), while the remaining portion comprises branched paraffin (isoparaffin) and cycloparaffin (Yao et al., 2022).

2.2. Wax Formation

The wax deposition process entails the creation, expansion, and accumulation of solid layers on the pipeline's inner surface. Wax deposition occurs exclusively when the pipe

surface temperature is lower than the wax appearance temperature (WAT). Researchers have researched various mechanisms, such as molecular diffusion, shear dispersion, and Brownian diffusion, to elucidate the formation of wax deposits on pipe wall.

Molecular diffusion refers to the movement of molecules from an area of higher concentration to an area of lower concentration due to random thermal motion. In the context of wax deposition, molecular diffusion occurs when wax molecules in the crude oil migrate towards the pipe wall, where the concentration of wax is lower. The concentration gradient drives this process, which takes place over time as molecules collide and exchange positions (Theyab, 2020). The rate of wax deposition can be explained by the following Eq. (1) (Burger, 1981).

$$\frac{dM_w}{dt} = \rho_w D_w A_w \frac{dC}{dr} \quad (1)$$

The diffusion coefficient can be formulated as follows in Eq. (2) (Burger, 1981):

$$D_w = 7,4 \times 10^{-9} \left[\frac{T_a (\xi M_{\text{solvent}})^{0.5}}{\mu_{\text{solution}} V_{\text{solute}}^{0.6}} \right] \quad (2)$$

Many diffusion coefficient models propose that the diffusion coefficient can be expressed as a function of the oil constant C1 and the viscosity of the oil. In simpler terms, Eq. (3) in several diffusion coefficient models indicates that the diffusion coefficient is influenced by both the oil constant C1 and the oil viscosity (Burger, 1981).

$$D_w = \frac{C_1}{\mu} \quad (3)$$

Shear dispersion is a mechanism that occurs when the flow of fluid within the pipeline causes mixing and dispersion of the components present in the fluid (Figure 2). In the case of wax deposition, shear dispersion occurs as a result of the shear forces exerted on the crude oil as it flows through the pipeline. These shear forces cause the wax molecules to disperse and mix with the bulk fluid, which can facilitate the transport of wax molecules towards the pipe wall (Huang et al., 2015).

Brownian diffusion, also known as Brownian motion, is the random movement of particles suspended in a fluid due to collisions with surrounding molecules. In the context of wax deposition, Brownian diffusion refers to the

random movement of wax particles within the fluid. This movement is caused by the thermal energy of the fluid molecules and can contribute to the transport of wax molecules towards the pipe wall, particularly in regions of low flow velocity where other mechanisms may be less effective (Azevedo & Teixeira, 2003).

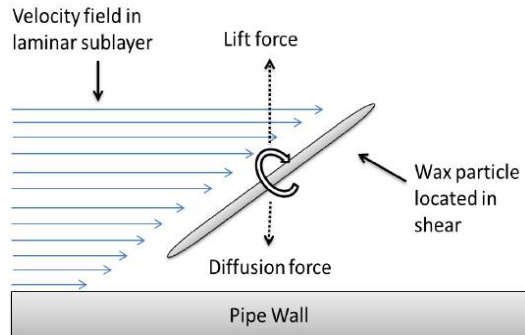


Figure 2. Long wax particle in shear dispersion mechanism

2.3. Thermal Remediation

There are two types of treatments in thermal methods for pipelines (González et al., 2018): passive thermal remediation using thermal insulation and active thermal remediation using heating systems. The heating systems commonly used include electric heaters and electric heat tracing systems. Heat tracing is a method to maintain the temperature of the pipeline and the flowing fluid by providing heat to the pipe to compensate for heat loss caused by lower ambient temperatures compared to the fluid temperature inside the pipe. Heat tracing can be achieved using various methods, including electrical, steam, glycol, and hot oil. The electric heat tracing methods studied in this document include constant wattage electric heat tracing, self-regulating electric heat tracing, and skin effect electric heat tracing (Bhatia, 2020).

Electric heat tracing is a pipe heating system that works by attaching heating cables to the exterior wall of the pipe. The heat generated by the cables helps maintain the temperature of the pipe and the flowing fluid inside. The heat produced by the cables is contained to prevent it from dissipating into the surrounding environment with the help of thermal insulation.

2.4. Electric Heater

The basic function of an electric heater is to generate heat using electrical energy. Electric heaters are designed to elevate the

temperature of high-viscosity crude oil. They are primarily used for the initial or additional heating of oil or water in the shipping industry. Their flexible design and wide range of heat outputs, ranging from 3 kW to 200 kW, require substantial electrical power, making it necessary to consider the availability of electrical supply for implementation (Bhatia, 2020).

2.5. Electric Heat Tracing – Constant Wattage

Resistive-type heating cables use a single or multiple resistive conductor material to create a heating circuit. The power and voltage output of these cables are relatively constant. The power output is determined by the combination of the cable length and the overall resistance of the conductor (Bhatia, 2020). Constant wattage heat tracing can be employed when the required heat output exceeds the self-regulating heater's capacity (self-limiting). This type of heating cable consists of two copper conductors (outer polymer jacket and mineral insulated cable/MI metal jacket) coated with insulation to form a heating element connected to two conductors at specific intervals, creating a heated zone.

Conductors and heating elements are equipped with one or more layers of magnesium oxide dielectric insulation and surrounded by an Incoloy 825 sheath (Figure 3). All insulation materials are made of heat-resistant and non-hygroscopic substances and should be covered with a tightly wound thin metal layer, covering at least 70% of the surface along with the outer polymer jacket.

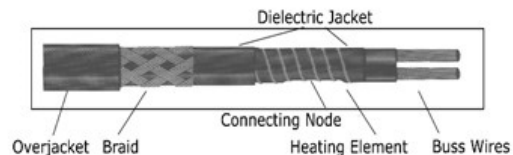


Figure 3. Constant wattage type cable

2.6. Electric Heat Tracing–Self Regulating

Heat tracing cable that are self-regulating, this cable is designed and constructed to adjust the power output and heat according to the required process design.

Self-regulating heat tracing cables are constructed with a nichrome resistance heating wire at their core, surrounded by a fluoropolymer insulating sheath for protection (Figure 4). Adjacent to the heating wire are fluoropolymer-insulated tinned copper bus wires, serving as electrical conductors. Inside, there's a fluoropolymer inner insulating layer

for added protection. A tinned copper grounding braid provides grounding, while a fluoropolymer over jacket shields the entire assembly. This construction ensures efficient and safe heat distribution, ideal for various industrial and commercial applications (Lardear, 1991).

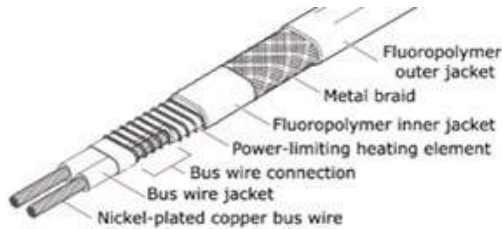


Figure 4. Construction of self-regulating cable

The operation of this type is very simple; when the temperature drops, the cable output increases, and conversely, when the temperature rises, the cable output decreases. This self-regulating characteristic allows the cable to adjust its wattage output at any point along the heater circuit (Bhatia, 2020). The temperature response occurs independently at each point along the heating element. This is read by the rheostat as a temperature function (both low and high-temperature changes) at every location within the element.

2.7. Electric Heat Tracing – Skin Effect

In this Skin-effect system, heat is generated by a single-core heat-resistant cable (non-magnetic, copper, or aluminum) installed within a ferromagnetic heat tube as shown in Figure 5. This heat tube is then thermally connected (welded) to the main pipe for heat transfer. For this type of heater, ferromagnetic material (heat tube) is attached parallel along the length of the pipe (Bhatia, 2020). At the end of the heating tube, the cable is connected to the alternating current supply as its power source, with a frequency of 50 Hz applied between the tube and the cable.

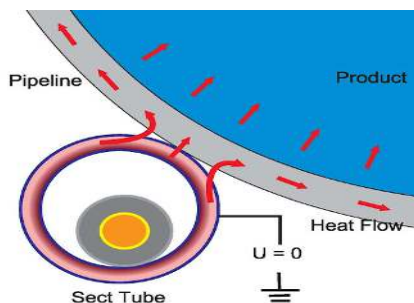


Figure 5. Construction of skin effect cable

The resistive effect of the cable generates heat, which propagates to the heating tube and then to the pipe. This action results in a power factor of approximately 90% of the total heat energy. This type of heater is one of the options suitable for underground pipe installations. In the event of a power failure, repairs and replacements can be carried out without excavation, making it a practical choice for such applications.

2.8. OLGA Simulation

The oil and gas industry widely uses Schlumberger OLGA, a multiphase simulation software, to model flow behavior in pipelines, wells, and production facilities. Its development history in Norway began in 1979 at the Institute for Energy Technology (IFE). Later, in 1987, development shifted to the Norwegian company Computer Modeling Group (CMG). Schlumberger acquired OLGA from CMG in 1995. Its function in transient analysis related to heat loss, wax deposition, etc. is to model and analyze temporary changes in pipeline systems and production facilities caused by factors like heat loss and wax buildup. Engineers can assess the impact of these changes on system performance and design effective solutions to address such challenges using OLGA. (Schlumberger, 2017).

The OLGA software is capable of simulating pipelines, whether they use insulation or have various layers with different thicknesses, heat capacities, and thermal conductivities. OLGA software calculates the heat transfer coefficient from the flowing fluid to the internal pipe walls; users specify the heat transfer coefficient on the outside, for example, with pipes partially buried at the seabed, where the average heat transfer coefficient must be determined. (Bendiksen et al., 2004). For the simulation, a carbon steel oil pipe is used with schedule 40 and size 4 inches. This oil pipe is coated with a 3mm thick 3LPE coating as illustrated in Figure 6 and buried in the ground to a depth of 1.5 m.

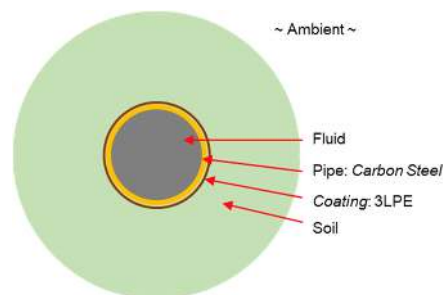


Figure 6. Illustration of radial heat transfer model

The heat loss can be calculated using the Eq. (4) (Institute of Electrical and Electronics Engineers, 2017).

$$q_{\text{loss}} = \frac{T_p - T_a}{\frac{\ln\left(\frac{D_2}{D_1}\right)}{2 \times \pi \times K_1} + \frac{\ln\left(\frac{D_3}{D_2}\right)}{2 \times \pi \times K_2} + \frac{1}{\pi \times D_4 \times h_a}} \quad (4)$$

The flow velocity in crude oil transmission pipelines can be calculated using the following derivative Eq. (5) (American Petroleum Institute, 1991).

$$V_1 = \frac{0.12 \times Q_1}{d_1^2} \quad (5)$$

During flow in a pipeline, friction occurs due to the fluid resistance against movement. Friction can be considered as energy that is "lost" or "dissipated" (converted into useless thermal energy) within the system. In a single-phase flow scenario, the friction component can be determined using the general Fanning equation in Eq. (6) (American Petroleum Institute, 1991).

$$\frac{\Delta P}{\rho} = \frac{4 \times f \times L \times V^2}{2 \times D} \quad (6)$$

The pressure drop fluctuates based on the length and diameter of the pipeline, velocity, fluid density, and the Fanning friction factor. The Fanning friction factor changes depending on the type of flow. Hence, by understanding the flow characteristics, whether laminar or turbulent, we can compute the value of "f" using Eq. (7) (American Petroleum Institute, 1991).

$$Re = \frac{\rho \times D \times V}{\mu} \quad (7)$$

2.9. Simulation Workflow

This research was carried out by adopting a methodology that can be represented as shown in Figure 7. The pipeline condition is predominantly submerged in swampy areas (80%) with a swamp ambient temperature of 77°F (Figure 8).

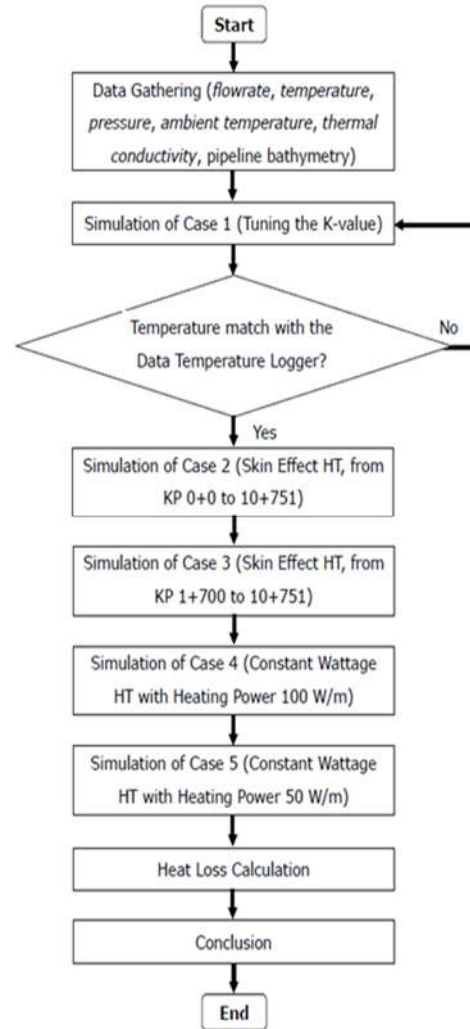


Figure 7. Flow chart of wax deposition prevention study methodology

Simulation case 1 tune the thermal conductivity (k) to match temperature logger data during pigging. If the OLGA simulation matches the logger data, cases 2 and 3 follow. Case 2 uses the skin effect to simulate heat tracing cable installation (start from KP 0+0 to KP 10+751). Case 3 is similar but covers only a pipe section (start from KP 1+700).

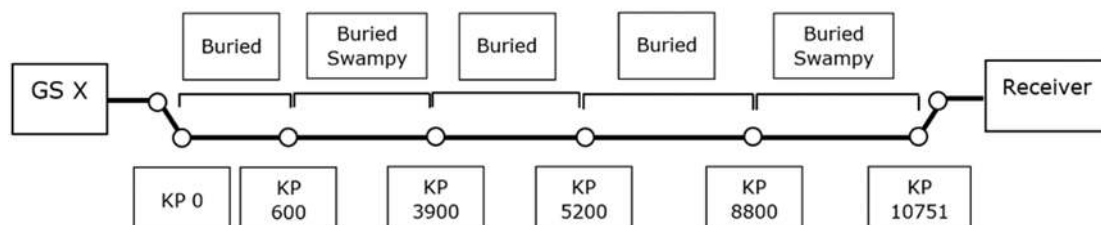


Figure 8. Scheme of the pipeline condition in segment X

Aerogel and glass wool (1 in and 2 in thick) insulate the carbon steel heat tracing cable (0.113 in thick). Heating power is between 10 and 15 W/m. Simulation cases 4 and 5 utilize constant-wattage heat-tracing cables with heating powers of 100 W/m and 50 W/m, respectively. Copper, with a thickness of 0.157 in, serves as the cable material, while aerogel and glasswool, with thicknesses of 1-inch and 2-inch, serve as the insulation. This heat tracing installation starts at KP 1+700.

The variables controlled in this simulation are pipe material, coating, pipe topography, and oil properties. Thermal conductivity and heating power are the independent variables manipulated to observe the changes that occur. Finally, the dependent variable or variables that are measured to see the influence produced by the independent variables in this simulation are the temperature profile of the oil and heat loss.

3. Results and Discussion

3.1. K-Value Tuning

This study conducted a trial to determine the appropriate thermal conductivity (k-value) for wet soil material. Figure 9 illustrates the relationship between temperature (y-axis) along the pipeline (x-axis) when crude oil is being transported. The temperature profile from simulation results compared to pigging results indicates a conservative outcome from the trial. The approach involved adopting two different thermal conductivity values (k-values), namely $K1 = 0.43 \text{ W/m.K}$ from KP 0+0 to KP 3+200, and $K2 = 0.575 \text{ W/m.K}$ from KP 3+300 to KP 10+751. These trial

results illustrate efforts to understand and optimize the thermal characteristics of wet soil, ultimately aiming to achieve more accurate and representative modeling of field conditions. After obtaining the thermal conductivity values from tuning and with an ambient temperature of 77°F, the tuning results were then analyzed by calculating the heat loss along the pipeline using Equation 4. The calculation results from the OLGA simulation provided a more optimistic outcome, indicating a heat loss of 26.45 W/m. This figure represents the heat loss along the pipeline at the end of the simulation. Meanwhile, the estimation results from IEEE, using Eq. (4), yielded a more conservative outcome of 26.91 W/m. This is because the calculation assumes a single thermal conductivity parameter for all soil types along the pipeline.

3.2. Skin Effect Heat Tracing – Whole Pipe

The graphs in Figs. 10 and 11 depict the changes in temperature (on the y-axis) along the pipeline (on the x-axis) concerning the heating power of the cable, the type, and the thickness of insulation used. The results from the temperature profiles demonstrate that both heating power and insulation thickness have a significant impact on maintaining desired temperatures along the pipeline. When employing heat-tracing cables with a heating power of 10 W/m and 15 W/m, coupled with aerogel insulation, the temperature at downstream KP 10+751 rises to approximately 148.35°F and 154.90°F, respectively, with a 1-inch insulation thickness.

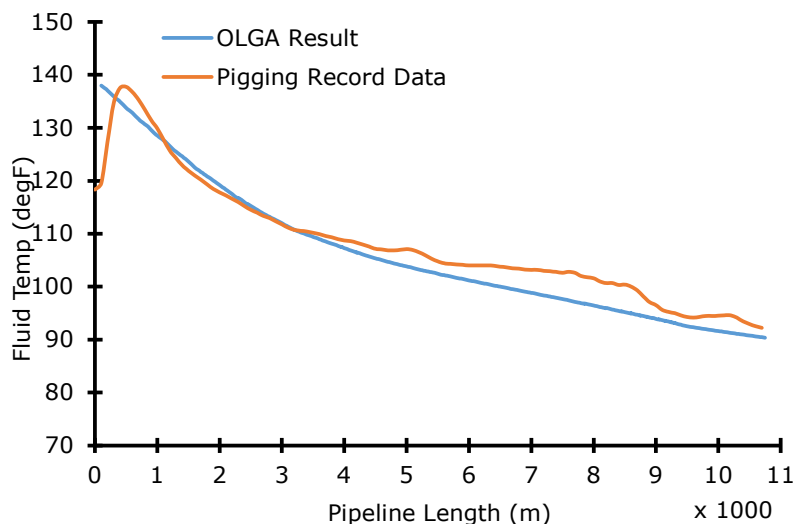


Figure 7. Temperature comparison between OLGA result vs pigging data

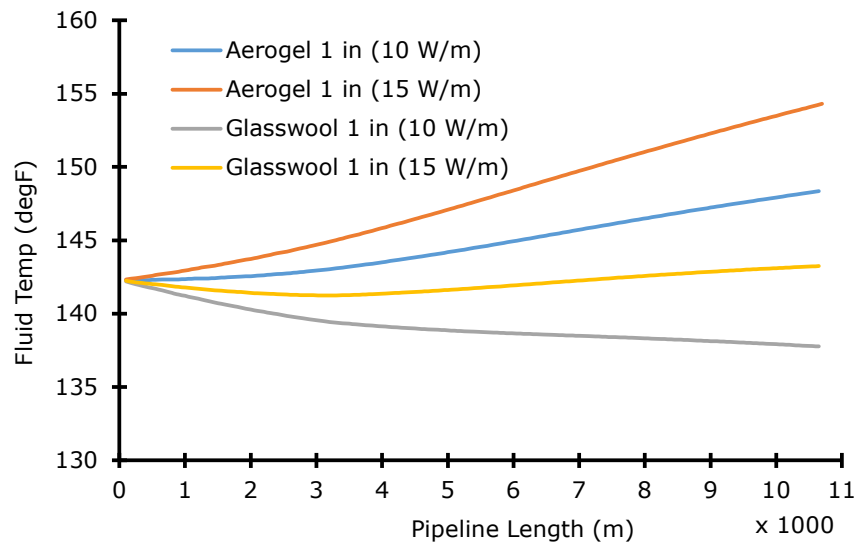


Figure 8. Comparison of simulation result with different heating power of skin effect heat tracing (whole pipe) with 1-inch thickness insulation

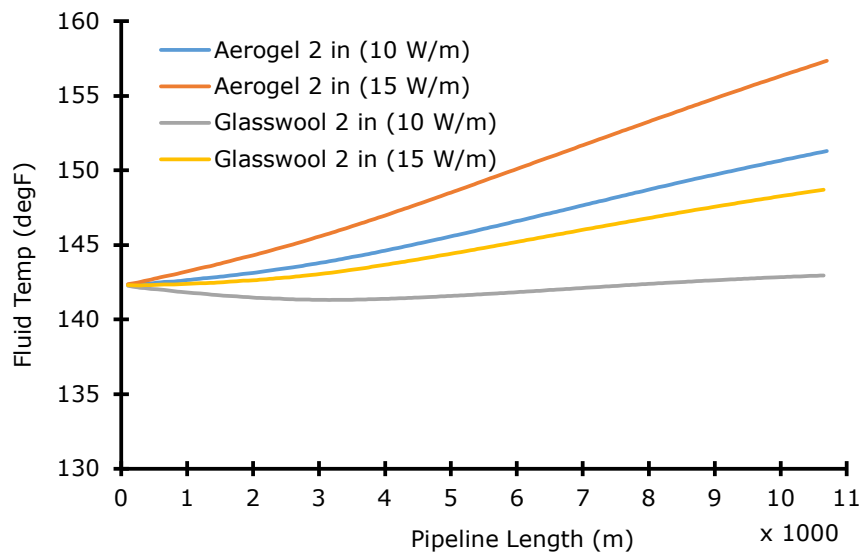


Figure 9. Comparison of simulation result with different heating power of skin effect heat tracing (whole pipe) with 2-inch thickness insulation

Increasing the insulation thickness to 2-inch elevates these temperatures to 151.29°F and 157.34°F.

In contrast, utilizing glasswool insulation with the same heating power yields lower temperatures at downstream KP 10+751, reaching around 137.77°F and 143.24°F with a 1-inch insulation thickness. However, increasing the insulation to 2-inch increases these temperatures to approximately 142.95°F and 148.69°F, respectively. Notably, the temperature profile with glasswool insulation consistently remains

lower than that with aerogel insulation due to glasswool's higher thermal conductivity.

To maintain temperatures above 115°F in a pipeline, a heating power of 15 W/m, aerogel insulation, and a 2-inch thickness are recommended. This configuration ensures effective heat loss compensation and temperature control, with the higher heating power counteracting heat loss. Aerogel insulation's superior thermal insulating properties minimize heat loss, resulting in higher temperature profiles. A 2-inch thickness further enhances temperature

maintenance. This combination maximizes temperature control, efficiency, and cost-effectiveness, making it the best choice for maintaining consistent temperatures.

3.3. Skin Effect Heat Tracing – Section Pipe

The graphs in Figs. 12 and 13 depict the changes in temperature (on the y-axis) along the pipeline (on the x-axis) concerning the heating power of the cable, the type, and the thickness of insulation used. The results underscored the pivotal role of heating power, insulation thickness, and insulation type in

temperature control and heat loss compensation. Among the configurations examined, it was determined that the most effective combination involved a heating power of 15 W/m and aerogel insulation with a thickness of 2-inch. This configuration consistently upheld temperatures above 115°F along the pipeline section, effectively addressing heat loss stemming from ambient and process conditions.

Simulation outcomes demonstrated that employing aerogel insulation with a 2-inch thickness resulted in crude oil temperatures at downstream KP 10+751 of 124.84°F and 127.18°F.

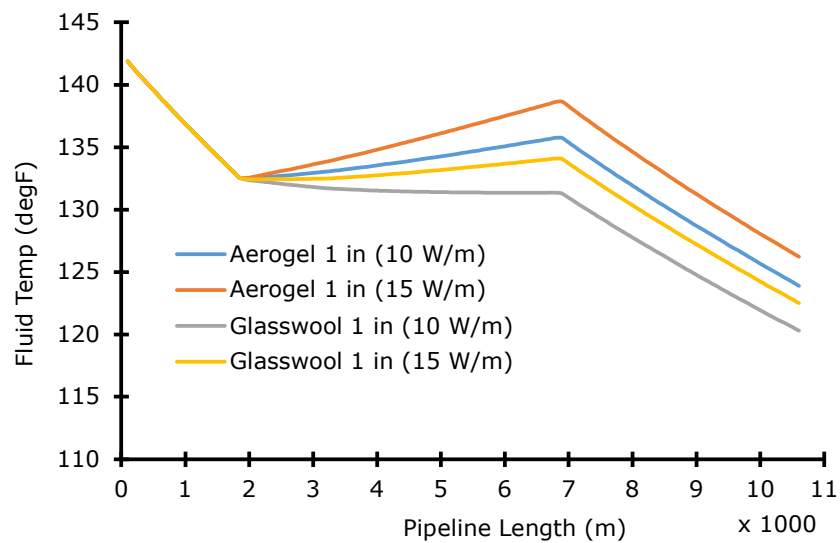


Figure 10. Comparison of simulation result with different heating power of skin effect heat tracing (section pipe) with 1-inch thickness insulation

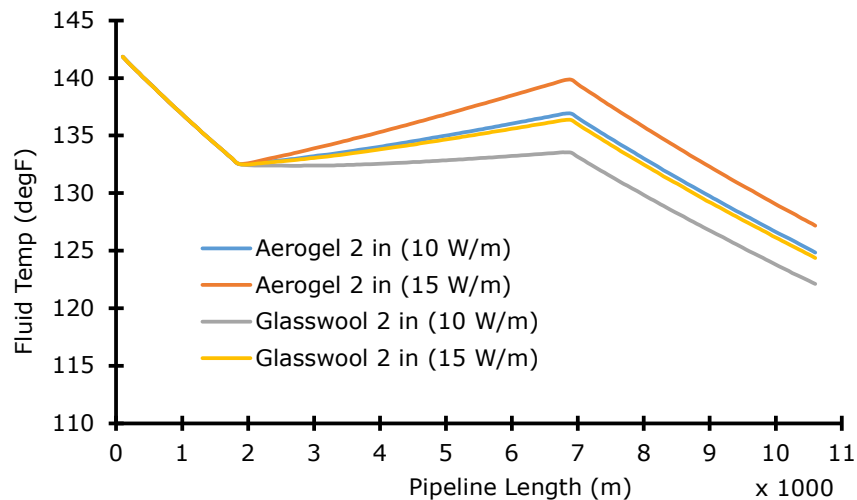


Figure 11. Comparison of simulation result with different heating power of skin effect heat tracing (section pipe) with 2-inch thickness insulation

In contrast, the use of glasswool insulation with the same thickness yielded temperatures of 122.10°F and 124.37°F. Despite the capacity of thicker insulation to mitigate heat loss, aerogel insulation surpassed glasswool due to its lower thermal conductivity, which contributed to reduced heat conduction and minimized temperature fluctuations along the pipeline section.

Comparing this simulation with previous results involving skin effect heat tracing applied to the entire length of the pipeline (Figs. 10 and 11) revealed similar trends in temperature maintenance. However, the localized application of heat tracing to a specific section facilitated a more targeted evaluation and optimization of heating power and insulation parameters, leading to improved temperature control and efficiency.

3.4. Constant Wattage Heat Tracing – Distance A (100 W/m)

The charts in Figure 14 illustrate variations in temperature (on the y-axis) along the pipeline (on the x-axis) based on the heating power of the cable, as well as the type and thickness of insulation employed. This case investigates the effectiveness of constant wattage heat tracing with a heating power of 100 W/m in maintaining crude oil temperature above 115°F along the pipeline section. The installation of constant wattage heat tracing is carried out with a maximum length of 1500m under low-temperature conditions (rain). The use of insulation types, namely aerogel and glasswool, is observed to determine which insulation configuration can reduce heat loss

to the environment. Figure 14 illustrates simulations using aerogel insulation with a 1-inch thickness. Initially, the heat tracing cable is installed at KP 1+700 – KP 3+200, but the crude oil temperature at KP 10+751 only reaches 105.82°F, still below the target temperature of 115°F. Subsequently, by adding heat tracing cable installation at KP 8+600 – KP 10+100, the temperature can be increased to 143.06°F, meeting the target temperature requirement. Simulations are also conducted with aerogel insulation of 2-inch thickness. Initially, the heat tracing cable is installed at KP 1+700 – KP 3+200, but it fails to maintain the temperature above the target temperature at KP 10+751, reaching only 106.13°F. Then, additional heat tracing cable installation at KP 8+700 – KP 10+200 increases the temperature to 145.48°F.

When using different insulation material, glasswool with a thickness of 1-inch and initial heat tracing cable installation at KP 1+700 – KP 3+200, the temperature at KP 10+751 reaches only 104.57°F. Subsequently, simulations are conducted with additional heat tracing cable installation at KP 8+200 – KP 9+700, increasing the temperature to 134.85°F, surpassing the target. Similarly, when using glasswool insulation with a thickness of 2-inch and initial heat tracing cable installation at KP 1+700 – KP 3+200, the crude oil temperature at KP 10+751 reaches only 105.23°F. Then, with additional heat tracing cable installation at KP 8+400 – KP 9+900, the temperature increases to 139.27°F, meeting the target temperature requirement.

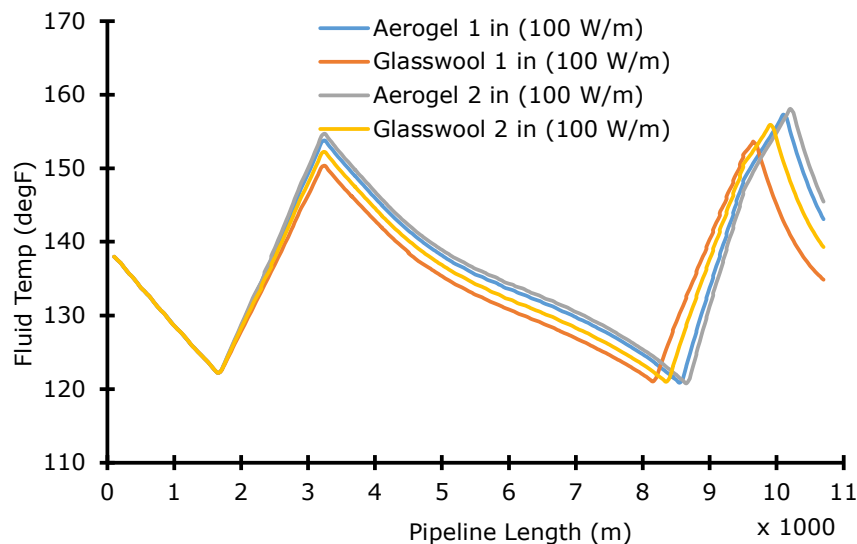


Figure 12. Comparison of simulation result with different insulation of constant wattage heat tracing with 100 W/m

As for insulation material, both aerogel and glasswool offer effective thermal insulation properties. However, the decision between the two depends on various factors such as cost, availability, and specific environmental conditions. In light of the given parameters, including the high WAT and the desired temperature maintenance above 115°F, the best option would likely involve using aerogel insulation due to its superior thermal resistance and lower thermal conductivity compared to glasswool. Thus, the optimal combination may entail a heating power of 100 W/m, coupled with 2-inch aerogel insulation of sufficient thickness to meet the desired temperature maintenance requirements.

3.5. Constant Wattage Heat Tracing – Distance B (50 W/m)

Figure 15 show how temperature (on the y-axis) changes along the pipeline (on the x-axis) in response to different heating power levels of the cable, as well as variations in insulation type and thickness used. In this case, transient simulation was conducted by installing constant wattage heat tracing along a 1500m stretch under low-temperature conditions (rain). The heating power utilized was 50 W/m, and the insulation materials employed were aerogel and glasswool, which are lower compared to the previous case of 100 W/m.

Transient simulation was carried out to observe the effects of installing constant wattage heat tracing insulated with aerogel (1-inch thickness) (Figure 15). Initially, with

installation at a single point along the 1500-meter span (KP 1+700 – KP 3+200), the temperature of the crude oil downstream at KP 10+751 could only be maintained at 99.83 oF, falling short of the desired target (>115°F). However, after re-simulation with installation at a second point along the 1500m stretch (KP 6+100 – KP 7+600), the temperature rose to 115.74°F. Utilizing insulation with a thickness of 2-inch, the temperature of the crude oil downstream at KP 10+751 increased to 100.12°F. However, this value remained below the desired target temperature. Therefore, a re-simulation was conducted with cable installation at the second point (KP 6+300 – KP 7+800). As depicted in Figure 15, the temperature of the crude oil downstream at KP 10+751 reached 117.19°F, exceeding the target temperature.

A transient simulation was also performed using a different insulation material, namely glasswool (1-inch thickness), with heat tracing cable installation at the first point along the 1500m stretch (KP 1+700 – KP 3+200). Using this type of insulation resulted in the downstream temperature at KP 10+751 only reaching 98.72°F. Therefore, a re-simulation was conducted with cable installation at the second point (KP 5+500 – KP 7+000).

The temperature of the crude oil downstream at KP 10+751 was 111.44°F. Since this remained below the target temperature (despite using 2 installation points), cable installation was added at a third point (KP 9+400 – KP 10+751). The temperature successfully reached 134.35°F, exceeding the target temperature.

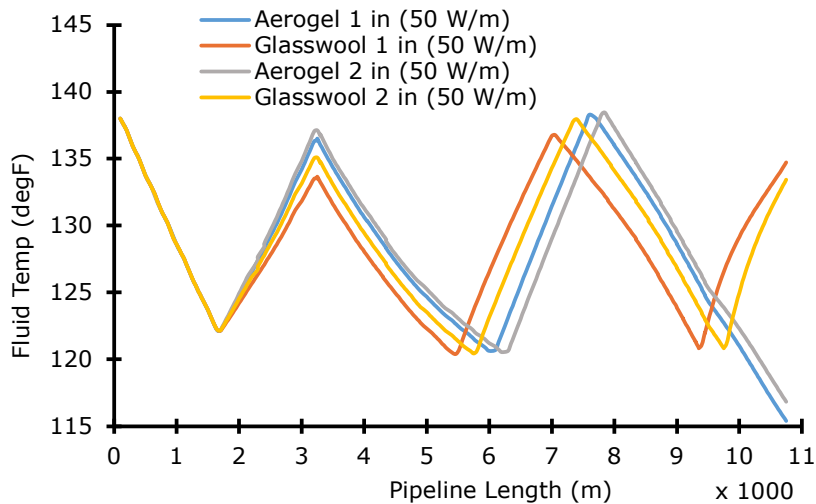


Figure 13. Comparison of simulation result with different insulation of constant wattage heat tracing with 50 W/m

When using thicker glass wool insulation, measuring 2 inches, it could only maintain the temperature of the crude oil downstream at KP 10+751 to 99.30°F, still below the desired target. Consequently, a re-simulation was conducted with cable installation at the second point (KP 5+800 – KP 7+300). Despite employing two installation points for heat tracing, the temperature of the crude oil downstream at KP 10+751 remained at 113.99°F, still below the target temperature. Thus, cable installation at a third point (KP 9+800 – KP 10+751) was executed. The temperature successfully reached 133°F, surpassing the target temperature.

In comparison to the installation with a heating power of 100 W/m, the installation with 50 W/m requires more points to increase the temperature at the downstream due to the reduced heating capacity per meter of the tracing cable (Figure 14). When the heating power is halved to 50 W/m, each meter of the tracing cable generates less heat compared to the 100 W/m scenario. As a result, the heat provided may not be sufficient to compensate for heat loss along the pipeline, especially over longer distances or under low-temperature conditions such as during rain. With a lower heating power, the temperature of the crude oil downstream may not reach the desired level (>115°F) with just one installation point. Therefore, additional installation points are needed to distribute the heat more effectively along the pipeline, allowing for better compensation of heat loss and ultimately achieving the target temperature.

Ultimately, the best combination would involve a balance between achieving the desired temperature, minimizing heat loss, and considering cost implications, with aerogel insulation (2-inch thickness) being the preferable option for maximizing thermal performance, provided it fits within the project's budget constraints.

Based on the simulation results, in Case 2, employing skin effect heat tracing along the entire pipeline length (from KP 0+0 to KP 10+751) with a heating power of 15 W/m and 2-inch thickness of aerogel insulation proved to be the most effective configuration for maintaining temperatures above 115°F, preventing the crude oil from reaching its PPT, and minimizing wax deposition.

In Case 3, focusing on a section of the pipeline starting from KP 1+700, a similar optimal configuration was identified, with the use of 15 W/m heating power and 2-inch thickness of

aerogel insulation to maintain temperatures above 115°F and prevent PPT conditions, resulting in a downstream temperature of 127.18°F.

In Case 4, employing constant wattage heat tracing with a heating power of 100 W/m, the optimal configuration involves using 2-inch thickness of aerogel insulation to achieve a downstream temperature of 145.48°F with two installation points, each spanning 1500m. In Case 5, with constant wattage heat tracing using a heating power of 50 W/m, the best configuration entails utilizing 2-inch thickness of aerogel insulation to attain a downstream temperature of 117.56°F with two installation points, each spanning 1500m. Alternatively, glasswool insulation with a thickness of 2-inch can also maintain the downstream temperature at 134.00°F, albeit requiring three installation points.

4. Conclusion

Based on the analysis of all cases regarding the use of skin effect heat tracing and constant wattage heat tracing, several in-depth conclusions can be drawn regarding the effectiveness of heating power, insulation type, and insulation thickness in compensating for heat loss in pipes and preventing wax deposition in the flowing crude oil. In Case 2 and Case 3, using skin effect heat tracing from KP 0+0 to KP 10+751, the use of heating cables with a power of 15 W/m and aerogel insulation with a thickness of 2-inch successfully maintained the downstream temperature above 115°F, while also preventing the crude oil from reaching its PPT at 102.2°F. The weakest result occurred when using 1-inch glasswool insulation and 10 W/m heating power, which could only maintain the downstream temperature at 137.77°F. When considering the theory to prevent wax deposition in pipes, it's crucial to ensure that the temperature inside the pipe remains above the wax appearance temperature (WAT), which in this case is 133°F. Additionally, it's important to avoid the pipe temperature reaching the PPT as it can cause the wax in the crude oil to solidify and coat the pipe, disrupting the flow. Among the four compared cases, Case 2 and Case 4 stand out as the best configurations for preventing wax deposition. This is because they can maintain the temperature above WAT and avoid contact with PPT, using the right combination of heating cables and 2-inch aerogel insulation. Case 3 and Case 5, which utilize constant wattage heat tracing, also play a role in maintaining pipe temperature, but they are

not as effective as Case 2 and Case 4 in preventing wax deposition because they focus more on downstream temperature without directly considering WAT and PPT. Thus, to prevent wax deposition in crude oil transportation pipes, configurations that maintain the temperature above WAT and avoid PPT, as found in Cases 2 and 4, are the most optimal choices.

Author Contributions

Conceptualisation, S.B.W.; Formal analysis, S.B.W.; Investigation, S.B.W., A.N.S., C.D.; Project administration, S.B.W.; Supervision, S.B.W., A.N.S., C.D., Writing – original draft, S.B.W., Writing – review and editing, S.B.W..

Acknowledgment

We would like to thank to Laboratory of Process System Engineering (PSE) – Department of Chemical Engineering, University of Indonesia.

Data Available Statement

Available on request to the corresponding author.

Conflict of Interest

There is no conflict of interest regarding the publication of this manuscript.

References

- Alnaimat, F., & Ziauddin, M. (2020) Wax Deposition and Prediction in Petroleum Pipelines, *Journal of Petroleum Science and Engineering*, 184, 1-2.
<https://doi.org/10.1016/j.petrol.2019.106385>
- American Petroleum Institute. (1991) *Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems*. American Petroleum Institute, Dallas.
- Azevedo, L. F. A., & Teixeira, A. M. (2003) A Critical Review of the Modeling of Wax Deposition Mechanisms, *Petroleum Science and Technology*, 21(3-4), 393-408.
<https://doi.org/10.1081/LFT-120018528>
- Bendiksen, K. H., Maines, D., Moe, R., & Nuland, S. (2004) The Dynamic Two-fluid Model OLGA: Theory and Application, *SPE Reprint Series*, 58, 52-61.
<https://doi.org/10.2118/19451-PA>
- Bhatia, A. (2020) *Heat Tracing Systems Credit: 4*. Continuing Education and Development Inc., New York.
- Burger, E. D. (1981) Studies of Wax Deposition in the Trans Alaska Pipeline, *Journal of Petroleum Technology*, 33 (06), 1075-1086.
<https://doi.org/10.2118/8788-PA>
- Felandry, D., Haq, M., & Farras, R. (2022) Implementasi Good Corporate Governance Dalam Kerjasama Antara PT. Pertamina Hulu Rokan Dan PT. Patra Drilling Contractor di Kecamatan Mandau Kabupaten Bengkalis Provinsi Riau. In *Jotika Research in Business Law* (Vol. 1, Issue 2).
<https://doi.org/10.56445/jrbl.v1i2.51>
- González, D., Stanko, M., & Golan, M. (2018) Numerical Feasibility Study of Electric Heating Strategies for Subsea Tie-In Flowlines Using a 1-D Mechanistic Multiphase Flow Simulator. *Engineering*, 10(09), 561-571.
<https://doi.org/10.4236/eng.2018.10940>
- Hamill, M., Chakkalakal, F., & Beres, J. (2017) Building the World's Longest Heated Pipeline-A Technology Application Review, *IEEE Transactions on Industry Applications*, 53(1), 709-717.
<https://doi.org/10.1109/PCIcon.2014.6961915>
- Huang, Z., Zheng, S., & Fogler, H. S. (2015) *Wax Deposition Experimental Characterizations, Theoretical Modeling, and Field Practices*, CRC Press, New York.
- Institute of Electrical and Electronics Engineers. (2017) *IEEE Std 515 – 2017*, IEEE Industry Applications Society, New York.
- Lardear, J. L. (1991) Control of Self-Regulating Heating Cable for Use in Pipeline Heating Applications, *IEEE Transactions on Industry Applications*, 21, 6-7.
<https://doi.org/10.1109/28.108468>
- Organization of the Petroleum Exporting Countries. (2023) *World Oil Outlook 2045 Organization of the Petroleum Exporting Countries*, OPEC, Austria.

- Ragunathan, T., Husin, H., & Wood, C. D. (2020) Wax Formation Mechanisms, Wax Chemical Inhibitors and Factors Affecting Chemical Inhibition, *Applied Sciences (Switzerland)*, 10, 479.
<https://doi.org/10.3390/app10020479>
- Rahmat, G., & Budisatya Wiranatanegara, M. (2021) Subsurface Geological Evaluation of the Central Sumatra Basin in Relation to the Presence of Heavy Oil, *Scientific Contributions Oil and Gas*, 44, 65-81.
<https://doi.org/10.29017/SCOG.44.1.491>
- Rehan, M., Nizami, A. S., Taylan, O., Al-Sasi, B. O., & Demirbas, A. (2016) Determination of Wax Content, Crude Oil, *Petroleum Science and Technology*, 34(9), 799-804.
<https://doi.org/10.1080/10916466.2016.1169287>
- Schlumberger. (2017) *Dynamic Multiphase Flow Simulator OLGA 2016: User Manual*, Schlumberger, Houtson.
- Sousa, A. M., Ribeiro, T. P., Pereira, M. J., & Matos, H. A. (2022) On the Economic Impact of Wax Deposition on the Oil and Gas Industry. *Energy Conversion and Management*, 16.
<https://doi.org/10.1016/j.ecmx.2022.100291>
- Thaher, Y. N. (2014) Pemodelan Deposisi Wax Pada Pipa Minyak Bawah Laut dan Strategi Mitigasinya, *M.S. Thesis*, University of Indonesia, Jakarta.
- Theyab, M. (2020) Study of Fluid Flow Assurance in Hydrocarbon Production-Investigation Wax Mechanisms, *PhD Thesis*, London South Bank University, London.
- Venkatesan, R., Nagarajan, N. R., Paso, K., Yi, Y. B., Sastry, A. M., & Fogler, H. S. (2005) The Strength of Paraffin Gels Formed Under Static and Flow Conditions, *Chemical Engineering Science*, 60(13), 3587-3598.
<https://doi.org/10.1016/j.ces.2005.02.045>
- Yao, Z., Zhang, Y., Zheng, Y., Xing, C., & Hu, Y. (2022) Enhance Flows of Waxy Crude Oil in Offshore Petroleum Pipeline: A Review, *Journal of Petroleum Science and Engineering*. 208.
<https://doi.org/10.1016/j.petrol.2021.109530>
- Yuan, Q., Luo, Y., Shi, T., Gao, Y., Wei, J., Yu, B., & Chen, Y. (2023) Investigation Into the Heat Transfer Models for the Hot Crude Oil Transportation in a Long-buried Pipeline, *Energy Science and Engineering*, 11(6), 2169-2184.
<https://doi.org/10.1002/ese3.1446>

Nomenclature

BI_{PPI}	Pour point index of component I (-)
C	Heat tracing cable circumference (m)
D_1	Inside diameter of pipe (m)
D_2	Outside diameter of pipe (m)
D_3	Outside diameter of coating (m)
D_4	Outside diameter of soil (m)
h_a	Convection ambient of air ($W/m^2 \cdot ^\circ C$)
k_1	Thermal conductivity of pipe ($W/m^2 \cdot ^\circ C$)
k_2	Thermal conductivity of coating ($W/m^2 \cdot ^\circ C$)
k_3	Thermal conductivity of soil ($W/m^2 \cdot ^\circ C$)
k_p	Heat conductivity of pipe ($W/m^2 \cdot ^\circ C$)
L	Pipe thickness (m)
PPI	Pour point temperature component I ($^\circ R$)
Re	Reynolds number (-)
T_a	Minimum ambient temperature ($^\circ C$)
T_f	Minimum fluid temperature ($^\circ C$)
T_p	Pipe maintenance temperature ($^\circ C$)
T_{sh}	Heat tracing cable surface temperature ($^\circ C$)
U_m	Overall heat transfer coefficient from cable to metal pipe ($W/m^2 \cdot ^\circ C$)
U_p	Overall heat transfer coefficient from cable to pipe system with non-metal coating ($W/m^2 \cdot ^\circ C$)
V	Fluid velocity (m/s)
W	Heating power provided to the heat tracing cable (W/m)
x_{vi}	Volume fraction of component I (-)
μ	Fluid viscosity (kg/m.s)
ρ	Fluid density (kg/m^3)