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# Effect of Solar Radiation and Soil Temperature on the Flow Characteristics in Above Ground and Underground Petroleum Pipelines

Tabarak M. Essa [1, *], Salman H. Hammadi [2]

[1,2] *Department of Mechanical Engineering, College of Engineering, University of Basrah, Basrah, Iraq*
*E-mail addresses: pgs.tabarak.majid@uobasrah.edu.iq , salman.hammadi@uobasrah.edu.iq*
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## Abstract

In this proposed study, all environmental factors affecting the aboveground and buried pipes, such as solar radiation and temperature, and soil temperature, have been studied on the characteristics of flow inside the aboveground and underground pipelines by building a mathematical model using MATLAB based on energy balance equations. From the mathematical model, the effect of solar radiation on the aboveground section of the pipeline is significate. During March and an inlet temperature of 34 °C, the pipeline outlet fluid temperature will rise to 50 °C. Other parameters affecting the aboveground section of the pipeline, such as ambient temperature and wind speed, have a much smaller effect on the fluid temperature, and the temperature difference is approximately 4 °C between the highest and lowest pipeline outlet fluid temperature. The result for the underground section of the pipeline showed that the main affecting parameter on the fluid temperature is the burry depth of the pipeline, the deeper the pipeline depth the lower the temperature variation and the lower fluid temperature can be seen, at 1 meter of bury depth the minimum and maximum fluid temperature was 18 °C and 36 °C respectively, and at 5 meters of bury depth, the minimum and maximum fluid temperature was 26 °C and 31 °C respectively. This study also checks different process parameters. Some of these are fluid flow, pipe diameter, and pipe material. The effect of the fluid flow and pipe diameter has a similar impact on the fluid temperature (while fixing all the other parameters), the higher the fluid flow or the smaller the pipe diameter resulted in a better heat transfer and more considerable temperature difference, and vice versa. The final process parameter, pipe material, had little to no effect on the fluid temperature variation.

***Keywords:*** Solar Radiation, Petroleum, Pipeline, Ambient temperature, Soil Temperature, Energy Balance.


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## 1. Introduction

Iraq is one of the countries that have the most oil wealth in the world. It has about 145 billion barrels of proven oil reserves, which puts it in fifth place on the global list [1]. Additionally, Iraq is one of the most prolific oil producers in the world. It now ranks fifth in the world with a production rate of 4.1 million barrels per day, which accounts for 4.6% of the total output worldwide. Approximately 3.55 million barrels of oil are shipped out of Iraq daily, equivalent to approximately 86% of the overall production rate [1]. The southern region of Iraq is home to most of the country's oil reserves. The oil fields of Majnoon, Nahr Umr, Zubair, West Qurna 1, West Qurna 2, Ratawi, and Rumaila are among the most important ones in the Basra region. Crude oil from these fields is processed by removing the gas in a central processing station known as Degassing Station. In these stations, associated gas and water are removed from the oil to meet the specifications necessary for export. Most processed oil in Iraq is moved from one location to another using aboveground and underground pipelines. Multiple main export pipelines run inside the border of Iraq and export oil to the surrounding countries.

Figure 1 depicts some of Iraq’s most important oil fields and the main export pipelines [2]. These pipelines are subject to the environment around them, including wind and solar energy in the case of the aboveground pipeline and the temperature of the soil in the case of the underground pipeline. The fluctuation in temperature that occurs along the length of the pipeline is a significant concern because it has the potential to affect the fluid characteristics and the temperature at the pipeline's exit.

Southern Iraq has a mainly arid and continental climate, with very hot summers and freezing winters. The region is known for its desert landscape. The months of December through March include a rainy season that lasts for three to four months, followed by a protracted dry season that lasts for the remainder of the year. During the summer months, there is very little precipitation, and there are frequent dust storms. The extremely highest recorded ambient temperature for a dry bulb is approximately 53 ºC, and the extremely lowest recorded ambient temperature for a dry bulb is approximately -2 ºC, [3] solar radiation can be absorbed and converted into useful forms of energy such as heat and electricity. The technical feasibility and economic viability of these systems in a specific place, however, is dependent on the available solar resource. Even though this heat has numerous benefits that can be honed, when a system needs to be isolated from any outside heat sources or the system's temperature needs to be kept within acceptable limits, the heat from the sun should also be carefully examined. Every region on the planet receives sunshine at some point during the year. The amount of solar radiation that reaches any given location on the Earth's surface varies as follows:

- Geographic location
- Time of day
- Season
- Local landscape
- Local weather.

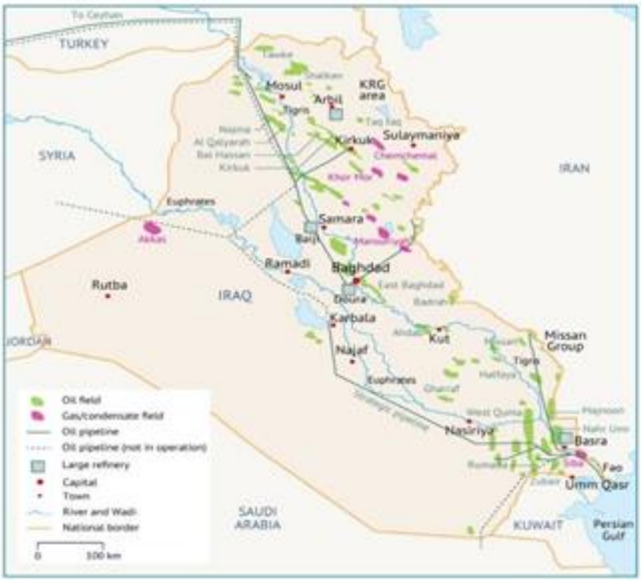


Fig. 1 Iraq’s main export pipeline

The main part of the previous studies focused on pressure rise inside the pipe due to solar radiation. It only focused on the aboveground or the underground section of the pipeline. The present study is an addition to the available studies in the literature. It provides extensive research on the affecting parameter that plays a part in the effect of the fluid temperature on oil export pipelines. Among the available studies, the work done by:

M. Murat Tunç (1985) [4] studied the development of a thorough numerical model considering a lumped capacity basis analysis for determining possible pressure rise in pipes caused by solar energy input. According to the calculations for water and gasoline, when there is no pipeline flow, the fluid's physical characteristics on time-dependent fluid and pipe temperature change, and pipeline pressure rise, reaching a level that could cause structural damage.

F. Al-Ajmia (2005) [15] studied the outlet air temperature and cooling potential of an earth-air heat exchanger in a hot, arid region by a model for Earth-Air Heat Exchanger (EAHE). This model's validity is checked against models published previously, which resulted in similar findings. A model for the soil temperature tailored to the unique circumstances in Kuwait City is provided, and the results are compared to observations taken at two different locations. The TRNSYS-IISIBAT environment has been used to encode all the models, and the model built to represent a typical home in Kuwait has been created. The air-conditioned cooling loads of the house with and without the help of EAHE were forecast using a typical Kuwaiti meteorological year. The EAHE might reduce the peak cooling demand by 1700 w and lower indoor temperatures by 2.8 °C during the summer peak hours, according to simulation results (during July). EAHE can reduce the cooling energy consumption in a typical Kuwait home by as much as 30% during the hot summer.

Mahmood Farzaneh-Gord (2010) [16] studied creating and providing a workable analytical model for predicting the temperature growth of incompressible flow within an aboveground pipeline. The outside of the pipeline is vulnerable to the sun's rays and the wind. Additionally, they consider the heat transfer that occurs through radiation with the surrounding environment. The emissivity and absorption of many exterior paint colors have been studied. The purpose of the model was to examine the fluctuation in temperature experienced by crude oil as it moved through a designated pipeline. It can be shown from the results of the model that the overall temperature reaches a maximum limit at a certain distance, and that this value is mainly affected by Reynolds numbers. It has been shown that in low Reynolds number flow, a pipe's surface absorptivity and emissivity significantly impact the temperature development of the pipe surface and the fluid inside. The findings suggested that the exterior paint color greatly affected the rate of temperature rise, suggesting that this factor should be considered when selecting an exterior paint color.

Y. El Mghouchi (2016) [17] Studied how solar radiation may be used to improve the process of designing energy systems relying on the sun, assessing thermal conditions, and coordinating the installation of various solar systems on a single structure. This research aims to evaluate four existing empirical theories from the literature: the Ghouard model, the Perrin Brichambaut model, the Bird and Hulstrom model, and the Capderou model. The statistical analysis was performed by contrasting computer simulation results with calculated values and information from a local energetic lab station. The collected findings show a spectrum of accuracy, suggesting that the examined models can reliably computer simulation results throughout the year. Daily diffuse, direct, and global solar radiation intensity under clear skies may be predicted using these methods for any given place on Earth, under this example in northern Morocco in Tetuan (35.57361 latitudes, 5.37528 longitudes).

Salman H. Hammadi (2018) [10] studied using an earth-water heat exchanger to temper water storage tank temperatures in hot climes areas; outdoor domestic water tanks are immediately exposed to a hot summer breeze stream and strong solar intensity. The temperature of the stored water rises above 50 °C. The research includes the water tank energy balance and the earth-water heat exchanger that lowers the water temperature in the summer season. An analysis of a time-dependent cylindrical home water tank exposed to extreme solar radiation is carried out to solve this issue. Fourth order Runge-Kutta method is used to solve the governing equations numerically. There was a good agreement when the numerical results were compared to the experimental data. The temperature of the water is found to be reduced by roughly 16 °C when utilizing an earth water heat exchanger.

Boris Moiseev (2017) [18] studied pipelines carrying oil operation in the frozen ground resulting in heat transfer between soil and the pipeline and the establishment of a melting zone, which causes the pipeline to deform. The circumstances of an oil pipeline's temperature significantly impact its design and functioning. In this sense, it's essential to understand the rules by which thawing halos around oil pipelines arise. Determining the best circumstances for the installation through construction in frozen zones north of the

Tyumen region and elucidating the laws governing the creation of thawing halos surrounding oil pipelines. The authors created computer software and technique for building the temperature field of the frozen earth. Several issues have been resolved based on the discovered dependencies, and graphs of the dependencies have been created. The authors were able to make recommendations for improving the reliability of oil pipelines thanks to their calculations and research on the construction of buried oil pipelines.

The main aim of this current study is to analyze all the factors affecting the aboveground and underground pipelines, such as Solar radiation, Ambient temperature, and Soil temperature, other additional case studies will also be investigated, these are:

1. Study the effect of fluid flow and pipeline diameter on temperature change.
2. Study the effect of pipeline construction materials and burial depth on temperature changes.

## 1. Theoretical analysis

This study considers a pipeline that transports oil from one location to another; a short portion of the pipeline is constructed aboveground while the majority of the length of the main pipeline is buried. As shown in figure 2, each portion of the pipeline will be affected by the surrounding environment, the solar radiation from the sun will heat the aboveground pipe wall which will heat the fluid flowing inside the pipe; another factor affecting the aboveground pipeline is the surrounding ambient temperature. On the other hand, the underground pipeline portion is affected mainly by the surrounding soil temperature which is a function of the pipeline burry depth. To achieve this study objective a numerical model has been built using MATLAB, the approach of using a numerical model only without backing the result with experimental data was due to the difficulties and challenges in providing the required reading on several kilometers of pipelines that carry oil which is considered a safety critical pipeline.

### 1.1 Aboveground and underground Energy Balance

The energy balance for the aboveground pipeline is derived as time-dependent by modelling a small slice from the pipeline as shown in figure 3. The underground pipeline energy balance is derived as length-dependent pipe wall temperature and fluid temperature at a given burry depth by modelling a small slice from the pipeline as shown in figure 4.

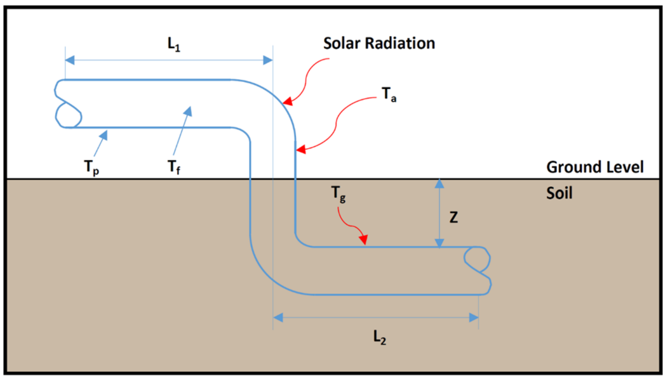


Fig. 2 Environmental condition on above and underground pipelines

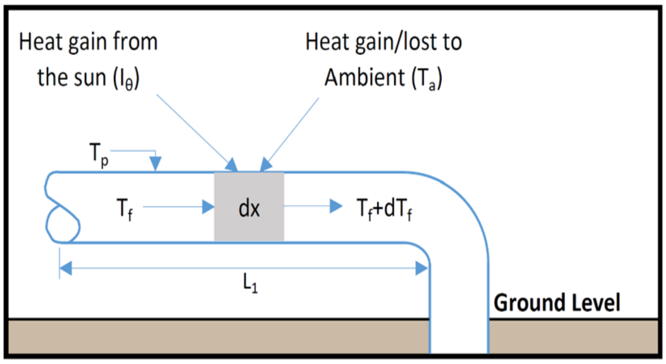


Fig. 3 Aboveground pipeline energy balance

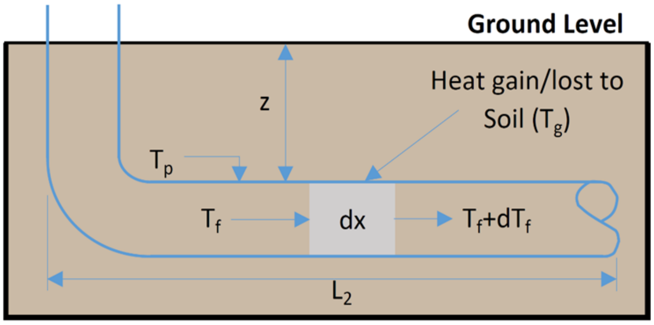


Fig. 4 Underground pipeline energy balance

The resulting energy balances are as follows:

Pipe, aboveground section [4]

$$\rho_p C_p A_p L_1 \frac{dT_p}{dt_s} = \frac{I_\theta \pi D_o L_1}{2} + h_o \pi D_o L_1 (T_p - T_a) - h_i \pi D_i L_1 (T_p - T_f) \quad (1)$$

Fluid, aboveground section [4]

$$\rho_f C_f A_f L_1 \frac{dT_f}{dt_s} = h_i \pi D_i L_1 (T_p - T_f) \quad (2)$$

The outside heat transfer coefficient ($h_o$) can be calculated from the following equation [5]:

$$h_o = 5.7 + 3.8 V_a \quad (3)$$

The inside heat transfer coefficient ($h_i$) can be calculated from the following equation [6]:

$$h_i = 0.023\, Re^{0.8}\, Pr^{N} \frac{K_f}{D_i} \quad (4)$$

Pipe, underground section [7]

$$m^o C_f \frac{dT_f}{dx} = \frac{T_g - T_f}{R_{conv} + R_{pipe} + R_{soil}} \quad (5)$$

Fluid, underground section [7]

$$m^o C_f \frac{dT_p}{dx} = \frac{T_g - T_p}{R_{conv} + R_{pipe}} \quad (6)$$

The heat equation for the soil can be expressed as follows [8]

$$\frac{1}{\alpha_g} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} \quad (7)$$

At z=0, $T_g(0,t) = T_m + A_s \cos\left\{\frac{2\pi}{8760}[t - t_o]\right\}$ **(8)**

At z=∞, $T_g(\infty,t) = T_m$

Solving equation 7 will give the soil temperature at different depths using the following equation [9]

$$T_g(z,t) = T_m - A_s\, exp\left[-z\left(\frac{\pi}{8760\,\alpha_g}\right)^{0.5}\right] cos\left\{\frac{2\pi}{8760}\left[t - t_o - \frac{z}{2}\left(\frac{8760}{\pi\alpha_g}\right)^{0.5}\right]\right\} \quad (9)$$

The value of the annual mean ground temperature ($T_m$) is 27 ºC, The value of the annual surface temperature ($A_s$) is 13.3 ºC, The value of soil diffusivity ($\alpha_g$) is 0.0038 $m^2$/h and The value of the phase constant ($t_o$) is 552 h [10]. Substitute the above value in equation 9 gives:

$$T_g = 27 - 13.3\, exp(-0.31z)\, cos\left\{\frac{2\pi}{8760}[t - 552 - 428.31z]\right\} \quad (10)$$

The three thermal resistances shown in equations 5 and 6 can be expressed by the following [9] [11]:

$$R_{conv} = \frac{1}{2\pi\, r_i\, h_i} \quad (11)$$

$$R_{pipe} = \frac{ln(r_o/r_i)}{2\pi\ K_p} \quad (12)$$

$$R_{soil} = \frac{ln(r_o/r_i)}{2\pi\, L_2\, K_g} \quad (13)$$

The ambient temperature $T_a$ can be represented as a sinusoidal function as shown below [12]:

$$T_a = \frac{T_{max} + T_{min}}{2} + \frac{T_{max} - T_{min}}{2} cos\left[\frac{\pi}{12}(t - 14)\right] \quad (14)$$

### 1.2 Total Solar Radiation

In equation 1, The total solar radiation on the pipeline is the rate at which solar radiation strikes the pipeline per unit area. This is provided by [13]:

$$I_\theta = I_{b\theta} + I_{d\theta} + I_{r\theta} \quad (15)$$

The direct solar radiation on a tilted surface ($I_{b\theta}$) can be calculated by:

$$I_{b\theta} = I_{DN}\, cos\theta \quad (16)$$

Several solar radiation models are available to calculate the direct normal solar radiation ($I_{DN}$). One of the commonly used models is the one suggested by The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the direct normal solar radiation ($I_{bN}$) can be calculated by the following equation [14]:

$$I_{DN} = A\, exp\left(-\frac{B}{sin\beta}\right) \quad (17)$$

Altitude Angle (β) is the angle between the sun's rays and the projection of the sun's rays onto a horizontal plane.

$$\beta = sin^{-1}[cosL\, cos\tau\, cos\delta + sinL\, sin\delta] \quad (18)$$

For any surface that is tilted at an angle Σ from the horizontal, the incident angle (θ), is given by:

$$\theta = cos^{-1}(sin\beta\, cos\Sigma + cos\beta\, cos\alpha\, sin\Sigma) \quad (19)$$

Figure 5 shows the definition of the Altitude angle and the Incident angle.

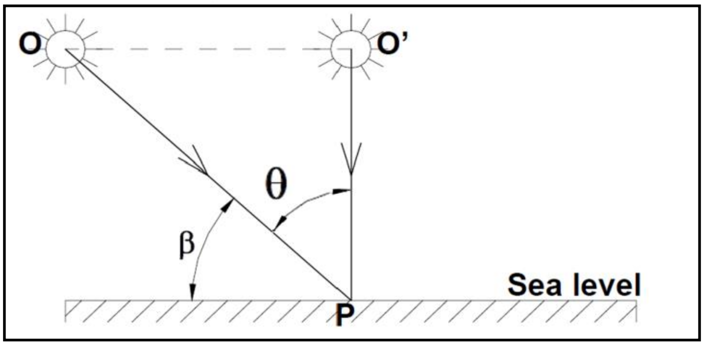


Fig. 5 Definition of Altitude Angle and Incident Angle

According to the ASHRAE model, the diffuse solar radiation from the cloudless sky ($I_{d\theta}$) can be calculated by [14]:

$$I_{d\theta} = C\, I_{DN}\, F_{WS} \quad (20)$$

The amount of solar radiation reflected from the ground onto a surface can be calculated by the following equation [13]:

$$I_{r\theta} = (I_{DN} + I_{d\theta})\rho_g\, F_{WG} \quad (21)$$

## 2. Results and discussion

Results of the theoretical analysis of the pipeline models for petroleum fluids: These fluids are deliberately chosen to stress the importance of the physical properties of the fluid on the time-dependent pipe and fluid temperature variations and the effect of solar radiation on the pipeline. The solar radiation will be calculated for the 21st day of each month of the year.

### 2.1 Aboveground Pipeline result

The maximum solar radiation happens during the solar noon when the sun is at the top, and the sun's rays have the shortest path to hit the specific point on the ground. The month of May has the highest solar radiation, December has the lowest. These findings are in-line with the result shown by the previous studies and the actual measured solar radiation, as shown in figure 6.

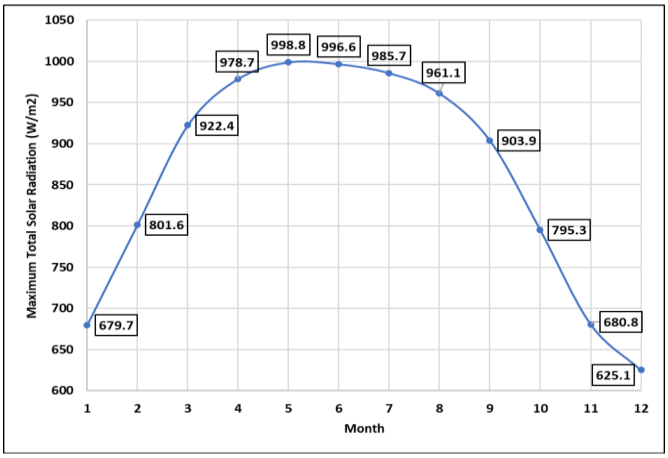


Fig. 6 Maximum Solar Radiation During the Year

The aboveground pipeline temperature during the night from hour 00:00 to sunrise time is only affected by the surrounding ambient and is a function of the ambient temperature, the pipe temperature is cooled to approximately the ambient temperature before it starts to rise again once the sun begins to rise, and solar radiation overcome the cooling from the surrounding ambient. The pipe temperature peak at around hour 15:00, and this is due to the heating effect from both the sun and the ambient, after hour 15:00, the pipe temperature starts to decrease, and this is because the amount of solar radiation from the sun begins to decrease. The pipe temperature starts to lose its energy to the surrounding again. The aboveground fluid temperature will match how the aboveground pipe temperature will be affected by solar radiation and ambient temperature and it will be similar to the pipe temperature but will be slightly lagging, figure 7 shows the ambient temperature, aboveground pipe, and fluid temperature variation during March.

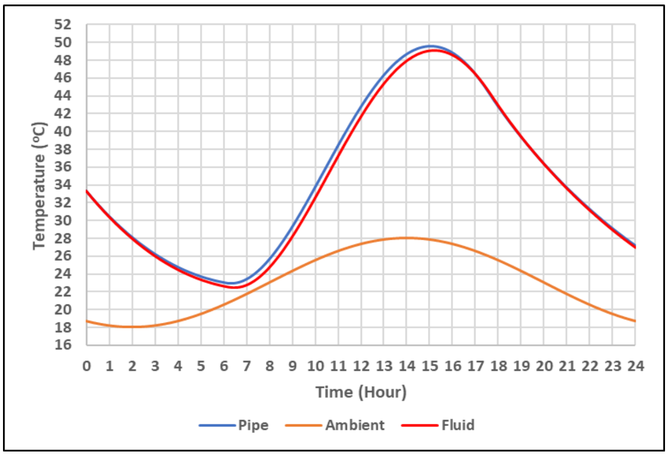


Fig. 7 Ambient temperature, aboveground pipe and fluid temperature as a function of time during March

The first case study on the aboveground pipeline will be the effect of different size pipelines, the result showing that the smaller the pipeline size the bigger the temperature fluctuation in the fluid temperature, this is the result of the highly turbulent flow inside the small size pipeline compared to a bigger sized pipeline, it can be understood that the efficiency of heat transfer is proportional to the fluid turbulence (i.e. the more turbulence, the better heat transfer efficiency). The same can be said for different value of flow rate at a fixed pipeline diameter, the more flow result in higher turbulence hence better heater transfer. Figure 8 shows the aboveground fluid temperature at different pipeline sizes during January.

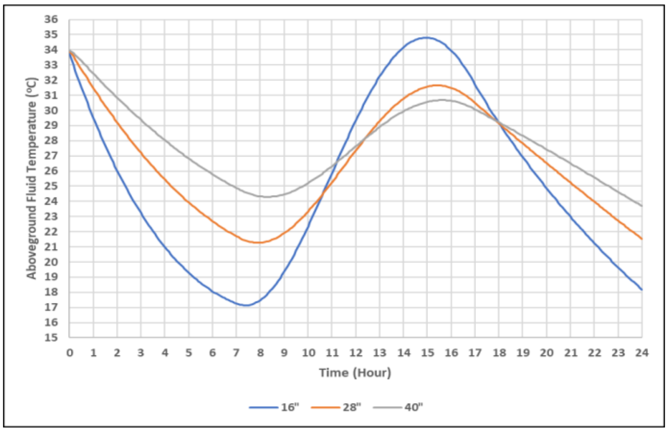


Fig. 8 Aboveground fluid temperature as function of time for different size pipelines during January

The second case study considered is the effect of the pipeline material on the fluid temperature, from figure 9 it can be noticed that both carbon steel and stainless-steel pipeline materials do not affect the fluid temperature.

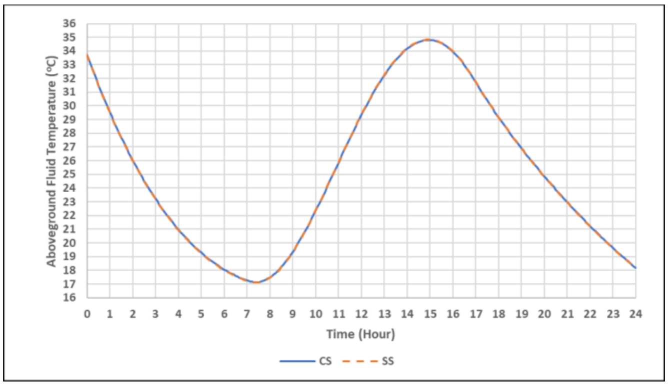


Fig. 9 Aboveground fluid temperature as function of time for different pipeline materials during January

## 2.2 Underground Pipeline result

The soil below the ground level is considered isolated from solar radiation and the ambient temperature, therefore it's considered fixed during a specific day, the only affecting factor affecting the soil temperature is the depth where the temperature is measured and the day of the year. From figure 10, it can be understood that the deeper the soil the less temperature fluctuation happens, this is due to the thickness of the soil layer above that work as an insulation from the solar radiation and the ambient temperature and vice versa, the smaller the burry depth, the bigger soil temperature fluctuation. From the same figure below, it can also be noted that with small bury depth the soil temperature maximum and minimum are in line with the seasonal change, the minimum temperature can be found in December and January and the maximum temperature can be found in June and July. But the deeper the burry depth, the effect starts to experience a lag in temperature change. The lowest temperature at 5 meters deep can be experienced in April and the maximum temperature is in October.

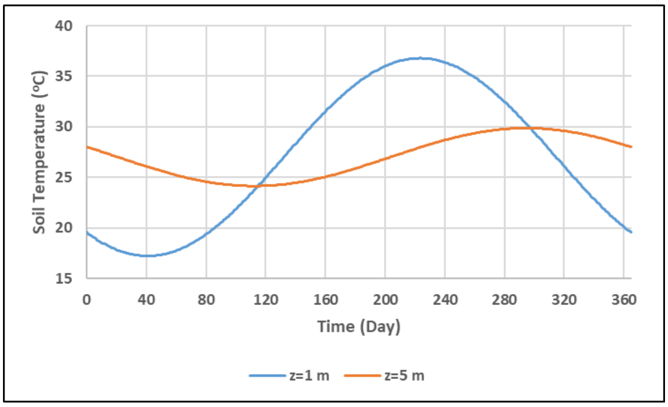


Fig. 10 Soil temperature at different depths

The underground pipe temperature is a function of the soil temperature which is a function of burry depth. The underground fluid temperature is also considered a function of the soil temperature, but the above variable affects the pipe wall temperature then in turn the pipe wall will act directly on heating or cooling the fluid inside the underground pipe, therefore, the fluid temperature is considered as a direct function of the pipe wall temperature. To fully understand how these factors are affecting the underground pipe and fluid temperature, the following result shows the pipe and fluid temperature as a function of time and as a function of pipeline length, the result will be shown throughout the year.

From figure 11, it can be noticed that the pipe temperature profile is very similar to that of the soil temperature and the fluid temperature profile matches the underground pipe temperature and is also very similar to that of the soil temperature.

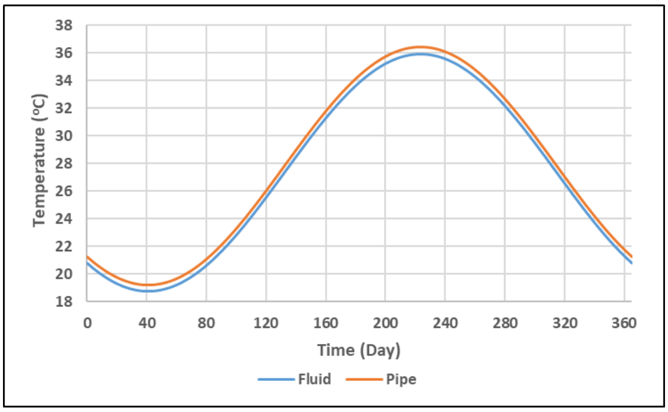


Fig. 11 Underground pipe and fluid temperature at a depth equal to 1 meter

From figure 12, it can be noticed that the pipeline length has a significant effect on the underground pipe and fluid temperature, unlike the aboveground pipeline portion. The underground pipe and fluid temperature will keep dropping until it reaches the soil temperature then it will create an equilibrium state with the soil temperature. Figure 12 shows the pipe temperature and fluid as a function of the pipeline length on a day in the month of March and the soil temperature on that same day at a fixed burry depth of 1 meter.

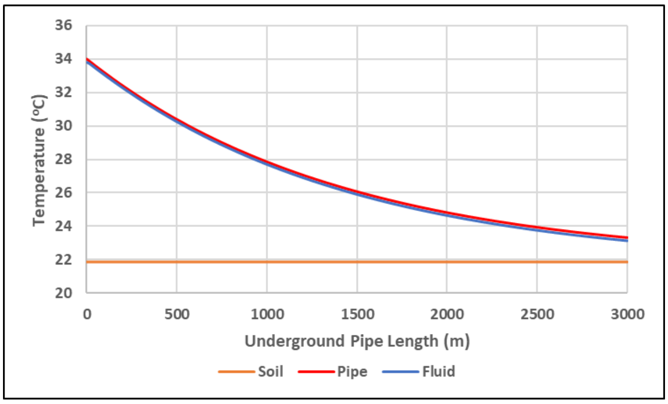


Fig. 12 Soil, underground pipe, and fluid temperature as function of length during March

Similar to what was noticed for the aboveground portion of the pipeline regarding the case study for the pipeline size, the small size pipeline will result in a higher turbulence flow and turn, result in a bigger underground fluid temperature fluctuation, this is shown as a function of length in figure 13.

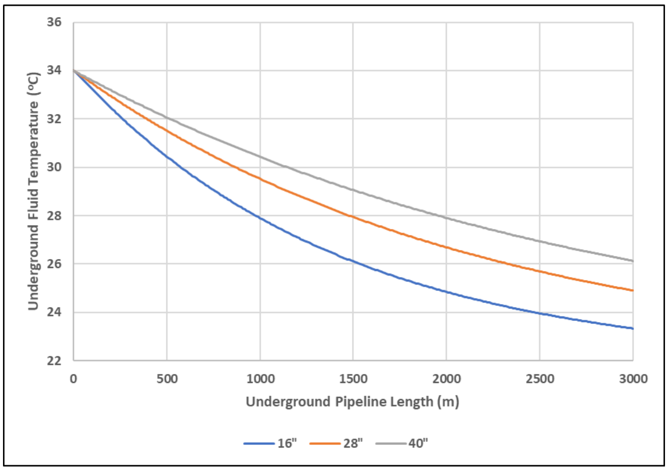


Fig. 13 Underground fluid temperature as function of length for different size pipeline during March

The effect of the flow rate on the underground fluid temperature is the opposite seen in the aboveground portion of the pipeline, the lower the flow rate the bigger the temperature fluctuation and vis versa. This is because, in the underground fluid temperature, there are multiple resistances to the heat exchange with the soil; the convection resistance which is the primary resistance affected by the flow turbulence plays a tiny part in the underground fluid temperature, and therefore with a small amount of fluid flow and low flow turbulence the fluid temperature fluctuation is high due to the small amount of fluid that requires a minimal heat from the soil to increase or decrease its temperature, this is shown in figure 14 as a function of length during the month of March.

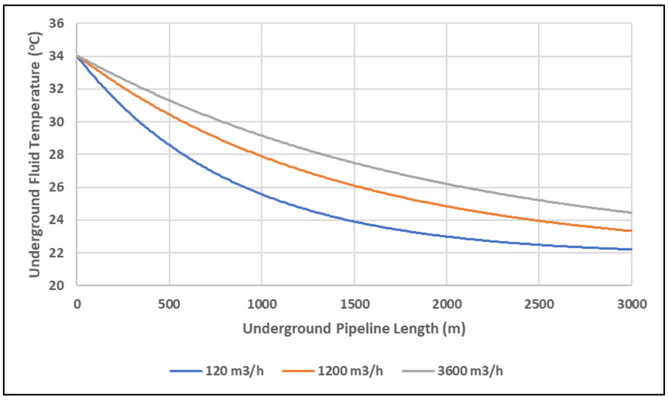


Fig. 14 Underground fluid temperature as function of length for different flowrate during March

Similar to the aboveground portion, the pipeline material has a minimal effect on the underground fluid temperature, figure 15 shows the underground fluid temperature as a function of length at two different pipeline construction materials, from the figure it can be noticed that the carbon steel pipeline has slightly higher temperature fluctuation that a stainless-steel pipeline.

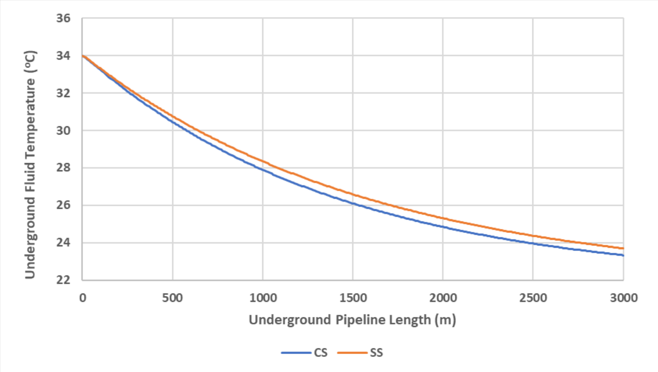


Fig. 15 Underground fluid temperature as function of length for different pipeline materials during March

The final case study is the effect of the pipeline bury depth on the underground fluid temperature; the result shows that the underground fluid temperature fluctuation increase if the burry depth is small; this is similar to the effect of the burry depth on the soil temperature, and because the two temperatures are linked together, therefore, it's noted that the change in the underground temperature due to burry depth is identical to that of the soil temperature, as seen in figure 16 as a function of time.

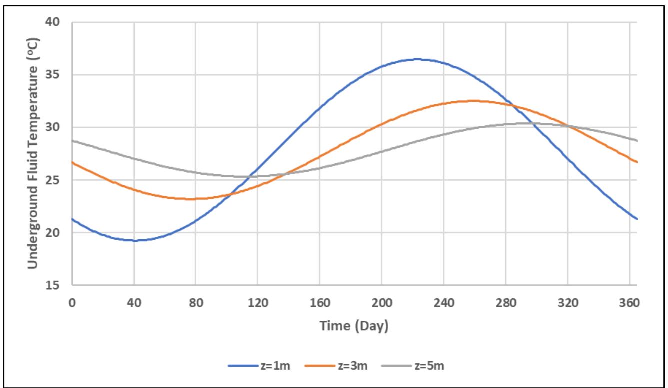


Fig. 16 Underground fluid temperature as function of time for different burry depth during March

## 3. Conclusions

From the result shown above, the effect of solar radiation in the aboveground section of the pipeline is more significant than the effect of the ambient temperature or wind speed. A fluid flowing through an aboveground pipeline will experience a moderate change in the fluid temperature for long pipelines, resulting in an arrival temperature at the destination similar to the source temperature.

For the underground section of the pipeline, the fluid temperature tends to increase or decrease reaching the soil temperature after approximately 4 kilometers for the fluid studied and the arrival temperature at the destination will be significantly affected by the type of soil and the bury depth of the underground pipeline.

The effect of pipeline diameter for both the aboveground and the underground portion of the pipeline is similar, with a small pipeline size, the fluid temperature will be significantly affected by the heat gain or loss to its surrounding, this effect is similar to the increase of flowrate when the pipeline size is fixed.

Both tested materials, carbon steel and stainless steel, show identical fluid temperature profiles due to the similarity in both material properties.

For the underground portion of the pipeline, the fluid temperature is greatly affected by the bury depth, the deeper the pipeline installation the lower the fluid temperature fluctuation but at the same time the lower the overall temperature.

## 4. Nomenclature

| Symbol | Description | Unit |
|---|---|---|
| $A_p$ | Pipe Wall Area | $m^2$ |
| $A_f$ | Pipe Cross-sectional Area | $m^2$ |
| A | Apparent Solar Irradiation | $W/m^2$ |
| $A_s$ | Annual Surface Temperature | °C |
| B | Atmospheric Extinction Coefficient | - |
| C | Constant for a Cloudless Sky | - |
| $C_f$ | Fluid-Specific Heat Capacity | kJ/kg.°C |
| $C_p$ | Pipe Specific Heat Capacity | kJ/kg.°C |
| $D_i$ | Pipe Inside Diameter | m |
| $D_o$ | Pipe Outside Diameter | m |
| F | Wall Solar Azimuth Angle Factor | - |
| $F_{WG}$ | Ground View Factor | - |
| $F_{WS}$ | View/Configuration Factor | - |
| $h_o$ | Outside Heat Transfer Coefficient | $W/m^2.°C$ |
| $h_i$ | Inside Heat Transfer Coefficient | $W/m^2.°C$ |
| $I_{b\theta}$ | Direct Solar Radiation on a Tilted Surface | $W/m^2$ |
| $I_{DN}$ | Direct Normal Solar Radiation | $W/m^2$ |
| $I_{d\theta}$ | Diffuse Solar Radiation | $W/m^2$ |
| $I_{r\theta}$ | Reflected Solar Radiation from the Ground | $W/m^2$ |
| $I_\theta$ | Total Tolar Radiation | $W/m^2$ |
| $K_f$ | Fluid Thermal Conductivity | W/m.°C |
| $K_g$ | Soil Thermal Conductivity | W/m.°C |
| $K_p$ | Pipe Thermal Conductivity | W/m.°C |
| L | Latitude angle | Degree |
| $L_1$ | Aboveground Pipe Length (m) | m |
| $L_2$ | Underground Pipe Length (m) | m |
| m° | Mass Flowrate | kg/s |
| N | Day Number During a Year | - |
| N | Prandtl Cooling/ Heating Constant | - |
| Pr | Prandtl Number | - |
| Q | Fluid Volumetric Flow | $m^3/s$ |
| $R_{conv}$ | The Convective Thermal Resistance | m.°C/W |
| Re | Reynolds Number | - |
| $r_i$ | Pipe Inside Radius | m |
| $r_o$ | Pipe Outside Radius (m) | m |
| $R_{pipe}$ | Thermal Resistance of the pipe | m.°C/W |
| $R_{soil}$ | Thermal Resistance of the soil | m.°C/W |
| $x$ | Pipe Length | m |
| $T_a$ | Ambient Temperature | °C |
| $T_f$ | Fluid Temperature | °C |
| $T_g$ | Soil Temperature | °C |
| $T_p$ | Pipe Wall Temperature | °C |
| $T_m$ | Annual Mean Ground Temperature | °C |
| $T_{max}$ | Maximum Monthly Ambient Temperature | °C |
| $T_{min}$ | Minimum Monthly Ambient Temperature | °C |
| t | Time | Hour |
| $t_s$ | Time | Second |
| $t_o$ | Phase Constant | Hour |
| $t_{rise}$ | Time at Sun Rise | Hour |
| $t_{set}$ | Time at Sun Set | Hour |

| | | |
|---|---|---|
| $V_a$ | Wind Velocity | m/s |
| $V_f$ | Fluid Velocity | m/s |
| z | Depth | m |

**Greek Letter**

| Symbol | Description | Unit |
|---|---|---|
| $\alpha$ | Wall Solar Azimuth Angle | Degree |
| $\delta$ | Declination Angle | Degree |
| $\tau_o$ | Hour Angle at Sun Rise and Sun Set | Degree |
| $\tau$ | Hour Angle | Degree |
| $\zeta$ | Surface Azimuth Angle | Degree |
| $\theta$ | Incident Angle | Degree |
| $\mu_f$ | Fluid Viscosity | Pa.s |
| $\rho_f$ | Fluid Density | $kg/m^3$ |
| $\rho_g$ | Ground Reflection Factor | - |
| $\rho_p$ | Pipe Material Density | $kg/m^3$ |
| $\Sigma$ | Tilt Angle | Degree |
| $\Psi$ | Zenith Angle | Degree |
| $\beta$ | Altitude Angle | Degree |
| $\Upsilon$ | Solar Azimuth Angle | Degree |
| $\alpha_g$ | Soil Diffusivity | m2/h |

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