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Weather Impact On Pipeline Temperature Distribution

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Abstract **-** Extreme weather conditions have shown significant impacts on pipeline safety, especially oil and natural gas pipelines. Floods, lightning, and extreme temperatures have been recognized as the most affected reasons for weather-induced pipeline damage. Among them, the extreme air temperatures, either extremely cold or hot, may not induce immediate damage to pipelines but may cause localized corrosion and fractures on pipeline segments impacted by extreme temperatures. Thus, it is of interest to understand how extreme air temperatures would influence the temperature distribution along the pipeline. As most pipelines are buried under soil, the influences of air temperatures on the pipelines are not direct. The property of the soil, the depth of the soil, and the temperature change rate will significantly impact such a temperature penetration. This study investigates and reviews how to convert the air temperature into the temperature distribution on the surface of the pipeline. Such a study can be used for further pipeline risk assessment and prediction.

Keywords**:** Pipeline safety, weather impact, temperature distribution

1. Introduction

Weather and natural forces such as extreme temperature events, rainfall, and lightning can significantly impact the pipeline safety. Among these weather events, the impacts from some such as rainfall and lighting impacts is difficult to well predict. While, some such as air temepraure either extreme cold or hot, can be predicted fairly in advanced. Thus, if there is approaches to predict how the air temperature events can influence the temperature distribution along the pipeline externally, it will assist the pipeline operators to understand how the air temperature impact the safety of pipelines and further assist the pipeline integrity management.

However, pipelines are usually buried underground. The influences from air temperatures to the pipeline external temeperature distribution depends significantly on the soil around the buried pipelines, which is accounted on the thermal conductivity of the soil. Thermal conductivity is a fundamental soil property that determines the heat transfer rate through the soil. It reflects the ability of the soil to conduct heat and is influenced by factors such as soil type, moisture content, and temperature. Natural forces can facilitate heat transfer in the soil, particularly under extreme weather conditions. Although thermal conductivity is a key factor in heat transfer, other soil properties, such as specific heat capacity and thermal diffusivity, also play important roles. Therefore, understanding soil thermal properties is essential for accurately modeling the temperature distribution of a buried pipeline and converting extreme air temperature to this distribution. Soil thermal properties, including thermal conductivity, specific heat capacity, and thermal diffusivity, are critical in determining the heat transfer rate from the surrounding soil to the pipeline. Extreme air temperature can cause temperature variations in the soil, which can then be transferred to the pipeline structure via conduction. By accounting for soil thermal properties in the pipeline design and operation, engineers can optimize the temperature distribution to minimize the impact of extreme air temperature on the pipeline. This ensures safe and efficient pipeline operation, reduces damage risk, and increases the lifespan of the pipeline infrastructure.

The objective of this paper is to review and understand what influence the soil thermal conductivity and how the pipeline operators can use limited knowledges on the air temperature to predict the external temepature distribution along the pipelines. Such an understanding will help the pipeline operators to investigate the influences from weather to the pipeline integrity and safety such as corrosion, temperature induced pipeline deformation, etc.

2. Properties influencing the soil thermal conductivity

There are many factors that influence the temperature penetration from the air through the soil to the underground pipelines, including air temperature, depth, moisture contents, dry density, soil type, and other factors. Air temperature determines the temperature difference between the air and the soil, which affects the heat transfer rate. The depth of the pipeline and the soil cover above it also play a crucial role in determining the temperature distribution, as deeper pipelines are less affected by changes in surface temperature. Gulser et al. (2004) showed that the highest fluctuations in soil temperature throughout the day occur at the surface, with the soil temperature at deeper depths (>30cm) remaining fairly constant throughout the day, only varying 1-2˚C [1].

Moisture content is another critical factor, as wet soil has higher thermal conductivity than dry soil, which can increase the rate of heat transfer to the pipeline. The experimental study performed by Malek et al. (2021), which utilized statistical methods for data analysis, demonstrated that soil water content significantly influenced soil thermal conductivity [1]. An increase in water content corresponded with a rise in soil thermal conductivity. The study also found that soil salinity played a crucial role in determining thermal conductivity. Becker et al. (1992) also yielded the same findings but also noticed that once the voids between the soil particles become completely filled with moisture (saturated soil), the soil thermal conductivity will no longer increase with an increase in moisture content [2]. They also found that the soil thermal conductivity also increases with the dry density of the soil due to the increased number of contact points between the soil particles, allowing increased heat flow paths. Thus, the dry density of the soil also influences the heat transfer rate to the pipeline.

Additionally, soil type is also an essential factor, as different types of soil have different thermal properties and respond differently to changes in air temperature. It was observed that silt-loam exhibited lower thermal conductivity values than the other soil types investigated by Malek et al. (2021) [1]. Hiraiwa and Kasubuchi (2000) conducted a study on the thermal conductivity of Ando soil and Red Yellow soil as a function of temperature and water content. The study found that thermal conductivity increased with both increasing temperature and volumetric water content, although not in a linear manner [3]. The soil mineralogy plays a role, as sands with quartz have higher soil thermal conductivity than sand with plagioclase feldspar and pyroxene. The soil thermal conductivity also varies little with the temperature at the ice point but highly varies between frozen and unfrozen states, solely due to ice having a higher soil thermal conductivity. The following model was created to describe the behaviors and was found accurate after analysis through error analysis models:

$$S = \lambda_1[\sin(\lambda_2 k + \lambda_3) - \sin(\lambda_4)] \quad (1)$$

where, S is saturation, λ_1, λ_2, λ_3, and λ_4 are coefficients dependent on soil type, and k is the soil thermal conductivity.

Tong et al. (2017) found that the thermal conductivity of soil increases as the sand particle size decreases [4]. This claim is supported by Becker et al. (1992), where it was found that the more points of contact the soil particles have with each other, the greater the soil thermal conductivity is [2]. And lastly, Tong et al. (2017) found that heat initially spread rapidly around the thermal storage well (due to the significant temperature difference in the soil), but the heat spread slowed as the temperature difference decreased over time [4]. Abu-Hamdeh et al. (2000) found that the sandy soil had higher thermal conductivities than any other soil at all bulk densities [5]. However, as bulk density increased beyond a certain point, loam and clay loam soils experienced a reduced rate of increase in thermal conductivity. Furthermore, the researchers investigated the impact of organic matter (peat moss) on soil conductivity and found that increasing the amount of organic matter in the soil actually led to a decrease in thermal conductivity [5]. Finally, other natural force factors, such as solar radiation and wind speed, can also affect the surface temperature of the soil and impact the temperature distribution of the pipeline. All of these factors must be taken into account when modeling the temperature distribution of buried pipelines and optimizing their design and operation.

3. Modeling pipeline external temperature distribution from air temperature

Modeling pipeline external temperature distribution from air temperature is essential because extreme cold or hot air temperatures may cause localized corrosion and fractures on pipeline segments impacted by extreme temperatures. Hu et al. (2011) found out that the soil temperatures closely follow that of air temperature, with the magnitude of variation decreasing with an increase in soil depth (time lag in peak values) based on their study on one year of data collected [6], as illustrated in Figure 1. Figure 1 reveals two distinct peaks in soil temperature near the bottom of the trench. The first peak, occurring between November and March, represents the minimum temperature, while the second peak, observed between April and October, represents the maximum temperature. In their study, Hu et al. (2011) observed that the peaks at deeper depths in the soil were later than (or lagged behind) the peaks in air temperature and were less extreme than those at or near the surface. The study also revealed that variations in water content generally decreased with increasing depth. It was noted from their study that sand typically maintained a degree of saturation of around 48%, whereas the mixed concrete exhibited significant fluctuations in water content [6]. A similar observation was obtained by Evett et al. (2012), where they also noticed that there is a delay or lag in temperature fluctuations at deeper depths, along with less drastic temperature variations at deeper depths compared to shallow depths [7].

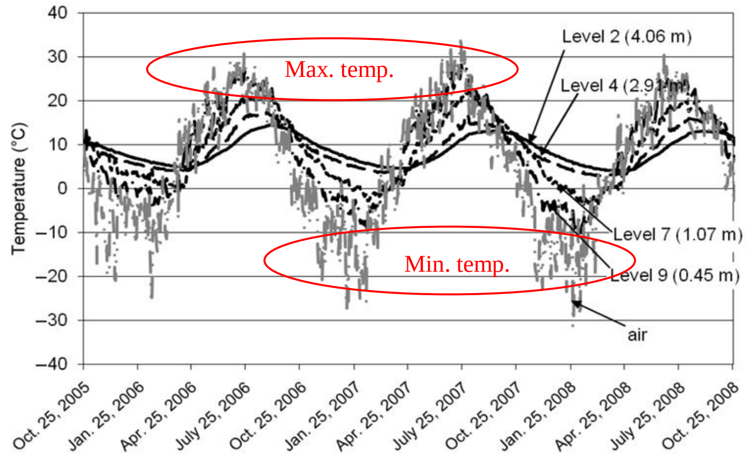

Figure 1. Temperature penetration through the soil to pipeline [Adopted from Ref. 6].

Another observation from Hu et al. (2011)'s study revealed that an increase in soil pressure caused the pipe to move downward, with the soil pressure correspondingly increasing as the frost penetrated deeper. Soil permeability significantly impacted the soil water content, while the pipe movement was measured to be around 20 mm. Although seasonal patterns were observed for the average longitudinal strains, the differential longitudinal strains remained relatively constant and were attributed to the high coefficients of thermal expansion of PVC (Polyvinyl Chloride) pipe and the seasonal changes in soil temperature. If the air temperatures were recorded and the soil properties along the pipelines were available, the diurnal temperature prediction using the sin-exponential model in Eq. (1) could be used to predict the temperature underneath the soil and along the pipeline (T_i) during daytime and nighttime using three simple parameters as [8, 9]:

$$\text{Daytime: } T_i = (T_X - T_N)\sin\left(\frac{\pi m}{Y+2a}\right) + T_N$$
$$\text{Nighttime: } T_i = T_N + (T_s - T_N)exp - \left(\frac{bn}{Z}\right) \tag{2}$$

where, T_i is the temperature at the *i*-th hour, T_x and T_N are the highest and lowest temperatures, T_s is the temperature at sunset, *Y* is the day length (hour), *Z* is the night length (hour), *m* is the number of hours after the lowest temperature occurs until sunset, *n* is the number of hours after sunset until the time of the lowest temperature, *a* is the lag coefficient for the highest temperature, and *b* is the nighttime temperature coefficient. This model assumes that the highest temperature will occur sometime during daylight hours and that the lowest temperature will occur within a few hours before or after sunrise. The sine-exponential model was also compared with other proposed models, such as the Fourier series model and a curvilinear model [8]. The Fourier series model equation is presented below.

$$T_i = a_0 + \frac{R_x}{R_0}\sum_{i=1}^{4}[a_i\cos(kit) + b_i\sin(kit)] \tag{3}$$

where, *k* is a Fourier constant describing the period of the temperature function, and a_i and b_i are the Fourier coefficients estimated with a standard algorithm (IBM-SSP program, FORIT, IBM, 1970). The average daffy temperature (a_0) and the observed diurnal temperature range (R_0) are determined from the observed maximum and minimum temperatures. The average annual temperature range (*Rx*) is determined by the data-fitting process. The order of the fitted series (*i*) was increased until either the additional sum of squares was determined insignificant by a Fratis test or until there was no further increase in the sum of squares (*i* never exceeded 4).

Although a curvilinear model was also presented for comparison [9], this model will not be elaborated further as it was not as accurate as the sine-exponential (Eq.(2)) and Fourier series models (Eq.(3)). The sine-exponential model requires only three parameters, while the Fourier series model requires eight parameters. The sine-exponential model also considers seasonal variation in day length and represents the diurnal temperature changes very well because of this and the combination of the sine wave and exponential function. When compared on an annual basis, the sine-exponential model was shown to be the most accurate, while the Fourier series model was most accurate when the data was parameterized monthly. However, even though the Fourier series model performed better on a monthly basis, and the sine-exponential model was a close second, overall, the sine-exponential model is the most accurate model for simulating diurnal temperature changes with parameters than the other models.

With the estimated external temperature distribution along the underground pipeline, the related literature also showed that the temperature distribution along the pipeline might significantly affect the corrosion rate of steel pipes, especially if the gradient of temperature change is high. Therefore, with the estimated external temperature distribution along the underground pipeline, pipeline operators and engineers can use the sine-exponential model to optimize the temperature distribution and minimize the impact of extreme air temperature on the pipeline. By taking into account the soil thermal properties and temperature distribution, pipeline operators and engineers can ensure safe and efficient pipeline operation, reduce damage risk, and increase the lifespan of the pipeline infrastructure.

4. Conclusions and future work

Previous studies have demonstrated that extreme air temperatures can significantly impact pipeline safety, particularly through the localized corrosion, temperature induced deformation, and fractures of pipeline segments. Understanding the soil properties that affect heat transfer rates, such as thermal conductivity, specific heat capacity, and thermal diffusivity, is critical for accurately modeling the temperature distribution of a buried pipeline and converting extreme air temperature to this distribution. Modeling pipeline external temperature distribution from air temperature can be conducted using the sine-exponential or Fourier series model. By accounting for these soil thermal properties in pipeline design and operation, engineers can optimize the temperature distribution to minimize the impact of extreme air temperature on the pipeline, ensuring safe and efficient pipeline operation, reducing damage risk, and increasing the lifespan of pipeline infrastructure. The practical implications of this study are that pipeline operators and engineers should consider the impact of extreme air temperature on pipeline safety and incorporate soil thermal properties into pipeline design and operation. Further research is needed to investigate the detailed relationship between extreme air temperature and soil temperature changes and improve pipeline risk assessment and prediction.

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