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THE INFLUENCE OF BURIAL DEPTH AND SOIL THERMAL CONDUCTIVITY ON HEAT TRANSFER IN BURIED CO_2 PIPELINES FOR CCS: A PARAMETRIC STUDY

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ABSTRACT

Pipeline heat transfer modelling of buried pipelines is integral to the design and operation of onshore pipelines to aid the reduction of flow assurance challenges such as carbon dioxide (CO_2) gas hydrate formation during pipeline transportation of dense phase CO_2 in carbon capture and storage (CCS) applications. In CO_2 pipelines for CCS, there are still challenges and gaps in knowledge in the pipeline transportation of supercritical CO_2 due to its unique thermo-physical properties as a single, dense phase liquid above its critical point. Although the design and operation of pipelines for bulk fluid transport is well established, the design stage is incomplete without the heat transfer calculations as part of the steady state hydraulic and flow assurance design stages. This paper investigates the steady state heat transfer in a buried onshore dense phase CO_2 pipelines analytically using the conduction shape factor and thermal resistance method to evaluate for the heat loss from an uninsulated pipeline.

A parametric study that critically analyses the effect of variation in pipeline burial depth and soil thermal conductivity on the heat transfer rate, soil thermal resistance and the overall heat transfer coefficient (OHTC) is investigated. This is done using a one-dimensional heat conduction model at constant temperature of the dense phase CO_2 fluid. The results presented show that the influence of soil thermal conductivity and pipeline burial depth on the rate of heat transfer, soil thermal resistance and OHTC is dependent on the average constant ambient temperature in buried dense phase CO_2 onshore pipelines. Modelling results show that there are significant effects of the ambient natural convection on the soil temperature distribution which creates a thermal influence region in the soil along the pipeline that cannot be ignored in the steady state modelling and as such should be modelled as a conjugate heat transfer problem during pipeline design.

1. INTRODUCTION

The pipeline transportation of single dense phase CO_2 for carbon capture and storage CCS has evolved considerably in the last two decades. Without doubt, it is an integral part of the CCS chain that can help climate change mitigation strategies and significant reduction greenhouse gas emissions. This paper highlights the background theory of heat transfer in buried pipes and then reviews previous studies done on the heat transfer in buried gas pipelines and a model case result of steady state heat transfer in dense phase CO_2. The physical phenomenon of the buried pipe system to calculate heat transfer buried pipelines is well established in literature and is essential during pipeline design and operation. This paper presents the results of the one-dimensional steady state heat transfer case study model of a buried dense phase CO_2 pipeline heat transfer analysis using the thermal resistance analogy under steady state conditions. The aim is to investigate the heat loss in an uninsulated pipe model with internal dense phase CO_2 at a fluid temperature of 40°C and ambient temperature of 15°C whilst paying particular attention to the OHTC together with the inner heat transfer coefficient values.

However, each field of application may vary significantly in design requirements and key parameters such as the thermo-physical properties of the working fluid, pressures, temperatures and flow rates. It is important to understand the key pipeline design criteria and operational requirements of CO_2 pipelines for CCS. These design parameters are significant both in the front-end engineering design and detailed design stages of the steady state and dynamic pipeline hydraulics and mechanical design of the onshore pipeline system for fluid flow assurance. Also, detailed description of the steady state temperature and pressure profiles along the entire pipeline length needed to achieve desired fluid arrival temperature required at the wellhead storage site. Depending on pipeline length, route and pipeline infrastructure adopted, CO_2 pipelines should be designed to account for pressure head losses, block valve, booster pump and compression locations to handle pipeline minimum pressures and maximum allowable operating pressure (MAOP) significantly above the critical point pressure of CO_2. This is imperative considering the effects of impurities to accommodate the flexibility to handle various CO_2 streams [1]. To this effect, and over the last two decades, significant research has been carried out relating to many design and operational aspects of CO_2 pipeline transportation for the safe design and operation of CO_2 pipelines [2-4] with Onyebuchi et al.(2018) providing a detailed review of previous research and key challenges surrounding the deployment of CO2 pipelines for CCS. Capture Power et al. (2016) as part of the White Rose Project provided a description of the proposed pipeline infrastructure and design that utilizes both a 12" and 24" nominal pipeline size (NPS) with a varied wall thickness along its route. This is to accommodate for future pipeline expansion capacity of dense CO_2 of up to 17 million tonnes per annum (MTPA), a first load supply of 2.68MTPA, and maximum injection capacity of 10MTPA together with confirming their engineering design rationale within design principles specified in recognized pipeline standard and code [5] of practice for CCS applications.

The heat transfer theory in buried pipelines is well documented in literature with (Bai and Bai, 2010) publishing the analytical solutions to thermal analysis and steady state heat loss calculation in oil and gas pipelines with OHTC and predictions of cool down time. As aforementioned, the underlying physics of the heat transfer mechanisms, heat loss and thermal resistance [6] in buried pipes and cylindrical geometries cannot be overemphasized in literature [7, 8] as it is fundamental to understanding the problem of heat transfer in a buried CO_2 pipelines. The most common approach for analytical solutions on the steady state heat transfer problem in buried pipelines is described in detail in [9]; [10]; [11]; [12] and [13].

Bau et al. (1982), studied a realistic situation in which the thermal interaction between the fluid flowing in the pipe and the solid medium in which the pipe is buried. Two cases were developed, one a realistic model which occurs in turbulent flow and assumes mixed convective boundary condition with a uniform heat transfer coefficient at the pipe surface and a second with fully developed laminar flow in the pipe. The laminar and turbulent cases were then compared with results including the temperature distribution inside and outside the pipe and the thermal resistances between the fluid and the surfaces as function of burial depth. Bau (1984), developed a regular perturbation expansion theory using the bi-cylindrical coordinate system to calculate the flow and temperature field associated with a pipe buried beneath an inclined surface. Schneider (1985), used finite element analysis to solve a heat loss from a buried pipe for which the boundary conditions at both the pipe surface and the ground surface are convective conditions connecting the pipe and ground to fluid and ambient temperatures.

More recently, Ovuworie (2010) presented approximate analytical solutions for steady state heat transfer for fully and partially buried pipes by solving the governing diffusion equation elegantly and by transformation to the bipolar cylindrical coordinate system used by Bau et al. (1982). He documented results to include and fully agree with temperature fields and shape factors for fully and partially buried pipe configurations [14]. Theoretically the conduction shape factor has been widely used to estimate heat losses in buried pipelines. The external pipeline to ambient heat transfer model is desired to correctly analyze and investigate the heat transfer rate and temperature distribution a buried pipeline with typical models limited to steady state heat transfer based on the conduction shape factor [15].

2. CO_2 PHYSICAL AND MATERIAL PROPERTIES

Pure CO_2 dioxide exist simultaneously in thermodynamic equilibrium at the triple point as a solid, liquid and gas phase at a temperature of -56.6 and pressure of 5.3bar respectively. CO_2 is a compressible gas that exists naturally in nature with unique thermo-physical properties that requires to be transported as a dense phase or supercritical single-phase fluid which occurs above its critical point. CO_2 occurs as a single phase fluid above its critical point pressure of 7.38MPa and 31.1°C temperature [16]. The dense phase CO_2 fluid thermo-physical play a major role in the design and operation of CO_2 pipelines due to the challenges associated with its dense and supercritical state required for pipeline transport for CCS. Figure 1 shows the pressure phase diagram of CO_2, above the critical point temperature and pressure, the liquid and gas phases do not exist as separate phases; liquid phase carbon dioxide develops supercritical properties where it possesses both characteristics of a gas and the density of a liquid. Specific considerations have been given to the fluid transport and thermo-physical properties of CO_2 for CCS pipeline transportation in literature to account for varying pipeline transportation scenarios during design and operation such as depressurization, pipeline shut down, temperature and heat transfer during pipe release [17] and Joule-Thomson cooling.

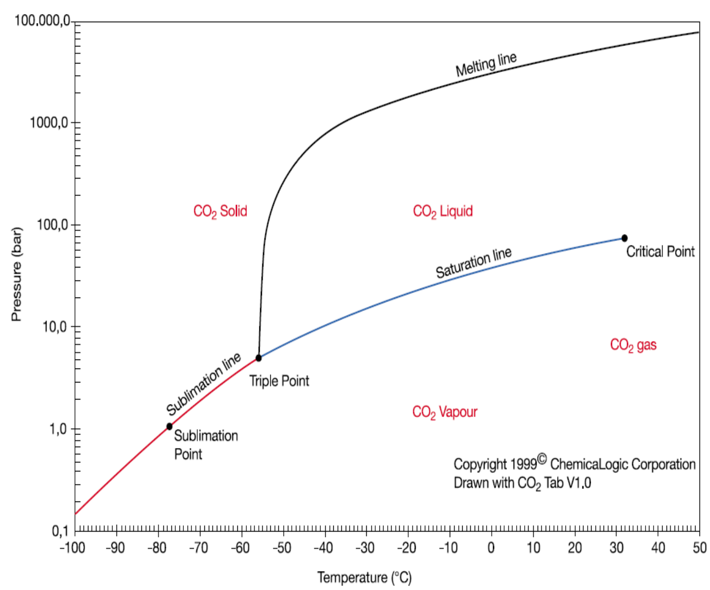

Figure 1: CO_2 Pressure - Temperature Phase Diagram [18]

A rapid decrease in the temperature of CO_2 in the pipeline will readily form hydrates which in the presence of water have the potential to block pipelines. The NIST Webbook Reference supplies the thermo-physical data of CO_2 at on a constant pressure curve over a specified temperature range compiled by the National Institute of Standards and Technology (NIST) under the Standard Reference Data Program Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) Version 7 [19].

Properties	Soil	Pipe	Air	Dense CO_2
Pressure (MPa)			0.101325	10
Temperature (℃)			15, 1.5	40
Density $\rho(\mathrm{kg/m^3})$	1200	7850	1.205	0.07141
Heat Capacity C_p (J/kg. K)	1480	490	1005	5657.5
Thermal Conductivity k (W/m K)	1.8	45	0.0257	628.61

Table 1: Material Thermal Properties

3. HEAT TRANSFER THEORY IN BURIED PIPELINES

The flow of CO_2 in a buried pipeline is a classic heat transfer problem where the temperature distribution in the system requires the coupling of the temperature and heat energy of the moving CO_2 to the temperature to the pipeline body over through it flows. When the temperature for the fluid is higher than the ambient temperature of its burial and ambient medium, the fluid is being cooled and vice versa i.e. when the temperature of the burial medium and ambient is higher than the temperature of the fluid in the pipe, the fluid is being heated. The heat transfer in buried pipes and pipelines transporting fluids for different engineering applications has been analytically, experimentally and numerically analyzed in various research publications. Whilst the underlying physics of heat transfer is common across most research fields, the approach and strategy can be different with major factors significantly affecting the results. Theoretically, the problem is a conjugate heat transfer problem because all three modes of radiation, convection and conduction heat transfer mechanisms are in situ. The heat transfer phenomenon in buried pipes can typically be described as;

- Forced convection of the fluid flowing inside the pipe.
- Heat conduction through pipe walls.
- Heat conduction through the homogenous soil burial Medium.
- Natural convection to ambient surroundings

In this study, heat energy is transferred through the soil to the ground surface and subsequently to ambient air from the pipe outer walls. The soil is a typical example of a semi-infinite porous media that contains fluids and fine-scale solid particles with pore spaces and although the physics of heat transfer through porous media is well established. This study focuses on heat energy transport through the homogenous soil region from a warm pipeline and the influence of thermal conductivity and burial depth. The rate of heat transfer between the pipe inner wall and the ground surface is directly proportional to the temperature differences and the total thermal resistance between the two surfaces. Therefore the rate of heat convection into the pipe inner wall from the CO_2 fluid is equal to the rate of conduction through pipe, soil and rate of convection from the soil surface to air. This is the heat transfer per meter length of pipe. However, considering the dense phase CO_2 in the pipeline is being cooled, there will be a change in the heat transfer rate due to the temperature difference between the fluid and the pipe inner wall. Therefore there will be a temperature drop as the dense phase fluid travels down the pipe. In this study, a number of assumptions have been made, they include;

- Steady state condition with no heat generation i.e. the rate of heat transfer remains constant and independent of time.
- Thermal conductivity is constant and homogenous.
- Temperature gradient is in the radial direction.
- External ground surface radiation from the air is negligible.
- The pipeline is uninsulated with isothermal conditions.

The temperature difference between fluid, pipe, soil and air governed by the Fourier law of heat conduction, newton's law of cooling and the law of conservation of energy.

The Fourier law heat equation governs the conduction of heat in buried pipes rate of heat conduction per unit area (heat flux) is directly proportional to the temperature gradient.

$$q = -k\frac{dT}{dx} \tag{1}$$

Where k is the thermal conductivity of material W/m.K, q is the Heat Transfer rate [(w) or J/s] and dT/dx = Temperature difference. For a one-dimensional heat flow through hollow cylinder geometry with the assumptions that the system is in steady state with constant isothermal properties with no heat source or heat sink in the system i.e. no thermal heat generation and the heat flows in the radial direction. Therefore the 1D Heat flux and temperature gradient through the pipeline geometry, the Fourier's law is written in the form in equation 2 [20]

$$q_r = -kA\frac{dT}{dr} \tag{2}$$

Where qr is the heat transfer rate, A is the area of the heat flow in the radial direction is A=2πrl

$$\frac{q_r}{2\pi rL}d_r = -kdT$$

$$\frac{q_r}{2\pi L}\int_{r_1}^{r}\frac{d_r}{r} = -k\int_{T_1}^{T} dT \tag{3}$$

$$\frac{q_r}{2\pi L}\ln\left[\frac{r}{r_1}\right] = -k\,(T - T_1)$$

Isolating to get T and arbitrary radial location r

$$T(r) = T_1 - \frac{q_r}{2\pi Lk}\ln\left[\frac{r}{r_1}\right] \tag{4}$$

To determine q_r using boundary conditions $T_i(r_i)$ and $T_0(r_0)$

$$q_r = \frac{2\pi Lk(T_i - T_0)}{\ln\left[\frac{r_0}{r_1}\right]} \quad (5)$$

For a one dimensional Heat flow through a hollow cylinder geometry with the assumptions that the system is in steady state with constant isothermal properties, there is no heat source or heat sink in the system i.e. no thermal heat generation and the heat flows in the radial direction. The thermal resistance concept is based on the electrical analogy to provide analytical solutions to heat transfer problems. By integrating eqn. (2) twice, separating the variables and applying two boundary conditions r_i and r_o to the pipeline radius, the rate of conduction heat transfer through a pipe of length L is

$$q = \frac{T_i - T_0}{\frac{ln\left(\frac{r_0}{r_i}\right)}{2\pi Lk}} \quad (6)$$

Heat transfer by convection is governed by the Newton's Law of Cooling which describes the rate of heat transfer as directly proportional to the temperature difference between a surface and fluid.

$$q = h(T_s - T_\infty) \quad (7)$$

Where q is the heat transfer rate, h is the convective heat transfer coefficient; T_s is the surface temperature and T_∞ fluid temperature. The internal convection coefficient hi of dense phase CO_2 in the pipeline is necessary to find the Reynolds number and Nusselt number and thermal resistance between the fluid and pipeline inner wall. Reynolds Number of CO_2 is derived using the fluid hydraulic properties at a pressure of 10MPa and 40°C as shown in the data table 1. It is therefore safe to say that the dimensionless value of the Reynolds number $ReCO_2 = D_i v\rho/\mu$ is dependent on the hydraulic parameters of pipeline diameter D, velocity of flow v, and the fluid thermal properties of density ρ, viscosity μ of the fluid. Therefore, to predict the heat transfer rate from the flow regime, the Reynolds number correlation is used to determine if the flow of CO_2 in the pipe is laminar or turbulent.

From the Reynolds number, Re > 2300, Prandtl number$0.5<P_r <120$ and pipe length L > 10D, the flow regime is assumed to be turbulent [8]. Hence, the Dittus-Boelter correlation $Nu=0.0255.ReCO_2^{0.8}.Pr^{0.3}$ is applicable. Where Nu is Nusselt number is $Nu = h_i.D_i/k_f$ and Inner film convection coefficient h_i can be written as;

$$h_i = 0.023.Re_{CO_2}{}^{0.8}.Pr^{0.3}.\frac{k_f}{D_i} \quad (8)$$

3.1 Thermal Resistance

The thermal resistance is the difference between the average pipe surface temperature and the ground surface temperature divided by the total heat flow rate. The conductive thermal resistance through the soil in which the pipe is buried, it is necessary to find the heat transfer coefficient through the soil for a buried pipe. In this analysis, the conductive thermal resistance R_p through pipe per unit Length of the pipe layer thickness. From Fourier's conduction heat in equation (2), the thermal resistance for a buried pipe using boundary conditions $T_i(r_i)$ and $T_0(r_o)$ for the inner and outer radius can be written as and calculated using equation (6)

$$R_p = \frac{ln(r_0/r_i)}{2\pi Lk} \quad (9)$$

The soil thermal resistance can be described as

$$R_s = \frac{r_2 * \mathrm{acosh}\left[\frac{2*Z}{D_2}\right]}{k_s} \quad (10)$$

Where R_s is the soil thermal resistance (W/m2K), Z is the pipeline burial depth to pipeline center (m), k_s is the soil thermal conductivity (W/m.K) and D is the pipeline reference diameter (m).

3.2 Overall Heat Transfer Coefficient

The heat transfer rate through a pipe section with Length L in eqn. (6) due to steady state heat transfer between the internal fluid in a buried CO_2 pipeline and the ambient can also be expressed as;

$$q = UA(T_i - T_0) \quad (11)$$

The overall heat transfer coefficient (U) can be written as;

$$U = \frac{1}{\frac{r_0}{r_i h_i} + \frac{r_0\, ln\left(\frac{r_0}{r_i}\right)}{k_1} + \frac{k_s}{\frac{D}{2}\cosh^{-1}\left(\frac{2Z}{D}\right)}} \quad (12)$$

Where A = 2πrL is the area of the heat transfer surface, h_i Inside film convection coefficient which is dependent on the fluid properties k_s is the soil thermal conductivity and z is the distance between the ground surface and the pipe center.

3.3 Conduction Shape Factor

The conduction shape factor concept for a buried pipe along with other shape factor configurations for the heat transfer rate for various geometry problems is presented in [21]. Where multi-dimensional heat conduction problems can be made simplified with analytical solutions depending on the shape of the system. Therefore, the rate of heat transfer is;

$$q = kS\Delta T \quad (13)$$

The shape factor for an isothermal horizontal pipe of length L buried in a homogenous semi-infinite region is; Where S is the shape factor, ΔT is the temperature difference.

$$S = \frac{2\pi L}{Cosh^{-1}\left(\frac{2z}{D}\right)} \quad (14)$$

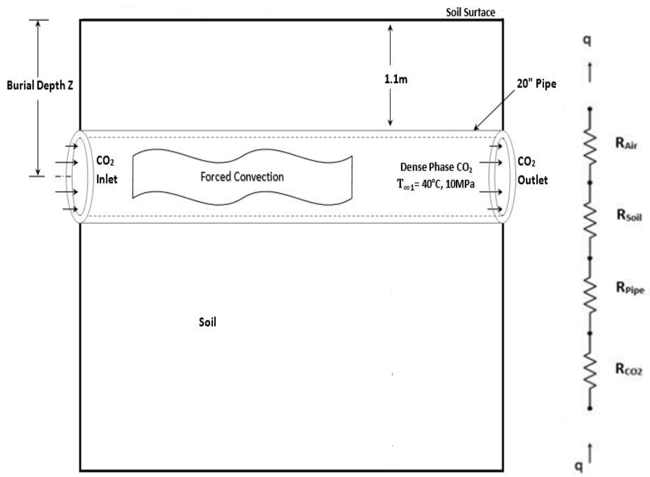

Figure 2: Lateral Representation of the Buried Pipe with Thermal Resistance Analogy

4. RESULTS

The steady state one-dimensional analytical model is based on a simple geometry of a meter length of steel pipe equivalent to a API 5L standard for an X65 20 inch pipe steel with resulting 0.508m outside diameter D2 buried at 1.1m from the ground surface to the pipe radial outer surface and coated with anti-corrosion coating. Pipeline parameters are represented in table 1 and figure 2 showing the material properties of CO_2, pipeline and soil used in this analysis. Dense phase CO2 fluid flows in the pipe at a velocity of 1.524m/s and temperature of 40°C and pressure of 10Mpa. It is assumed to be isothermal with internal and external convection to the fluid, soil and ambient air at 1atm of 15˚C respectively. It is assumed that external soil surface radiation to the air is negligible, as such external convection coefficient to air is also assumed to be negligible. Model data parameters used for this analysis is inputted into Mathcad with analytical solutions for the above equations presented in the results below in in SI units.

For a comprehensive parametric study of the pipeline burial depth Z(m) i.e. soil surface to pipeline center and the soil thermal conductivity k_s (W/m.K), the Z and ks values are varied. The Z values are varied from an initial burial depth of 1.1m to 2.7m at intervals of 0.2m while the thermal conductivity ks values of the soil are varied from 1.1 W/m.K to 2.0 W/m.K with an initial value of 1.8 W/m.K. Results are then generated for OHTC, Soil thermal resistance and heat loss at each of the varied corresponding burial depth and soil thermal conductivity values. Although, this study is independent of pipeline thermal insulation, this helps to emphasize the influence of the pipeline burial death and thermal conductivity on heat transfer in a greater detail. The effects of thermal insulation on the pipeline thermal resistance and OHTC values in the pipeline transportation of bulk fluids is advantageous in reducing the heat loss from the pipeline fluids. This is because pipeline thermal resistance and OHTC values between a pipeline fluid and the soil burial medium increases with the presence and thickness of a thermal insulation layer. A few factors mitigate against the temperature drop along dense phase CO_2 pipelines. This include the fluid property requirement to be transported as a dense phase or supercritical fluid above its critical point as discussed in section 2, the ambient temperatures, average annual ground conditions as climatic conditions vary with location of the pipeline. However, the maximum transportation distance before pressure and temperature drop below safe critical temperature and pressure can be affected. This is can be accounted for with higher inlet pressure and temperatures, compressor and booster stations along pipeline route depending on the cost-effective solution adopted for any particular CO_2 pipeline infrastructure.

4.1 Effects of Pipeline Burial Depth

The steady state results to analyses the effects of pipeline burial depth and thermal conductivity on the soil thermal resistance, heat transfer rate and the (OHTC) on a buried dense phase CO_2 pipeline using parameters in table 1. The results presented in figures 3, 4 and 5 below. For the 1-D model, Figure 1 shows a plot of the varied pipeline burial depth against the corresponding heat transfer rate for both 1.5°C and 15°C ambient temperatures. The heat transfer rate reduces with increasing pipeline burial depth at higher ambient temperature of 15°C while the heat transfer rate increases significantly at low ambient or surface temperatures of 1.5°C. However, as shown in figure 5 below, an increase in pipeline burial depth increases soil thermal resistance and decreases the overall heat transfer coefficient (OHTC). Also changes in the ambient or soil surface temperature does not affect the total thermal resistance or the OHTC.

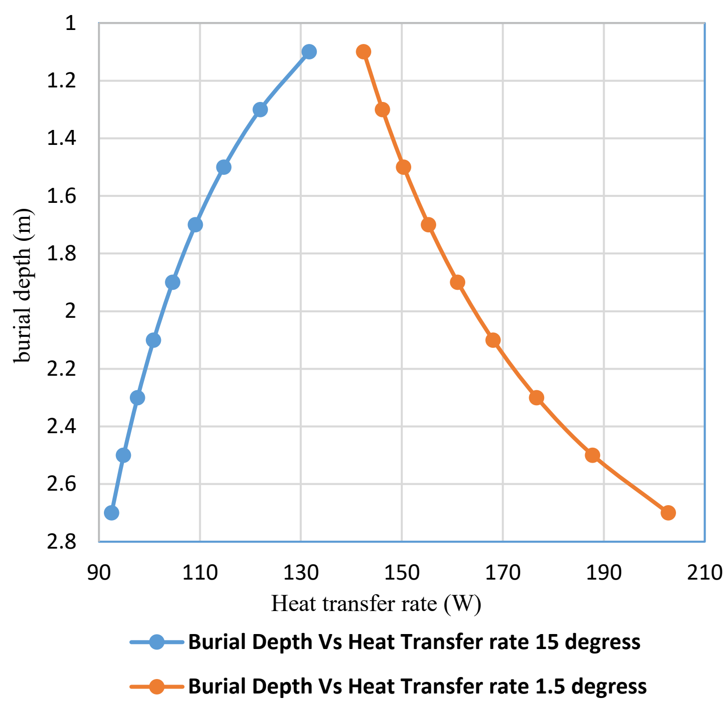

Figure 3: Shows burial depth Vs heat transfer rate using the 1D steady state model

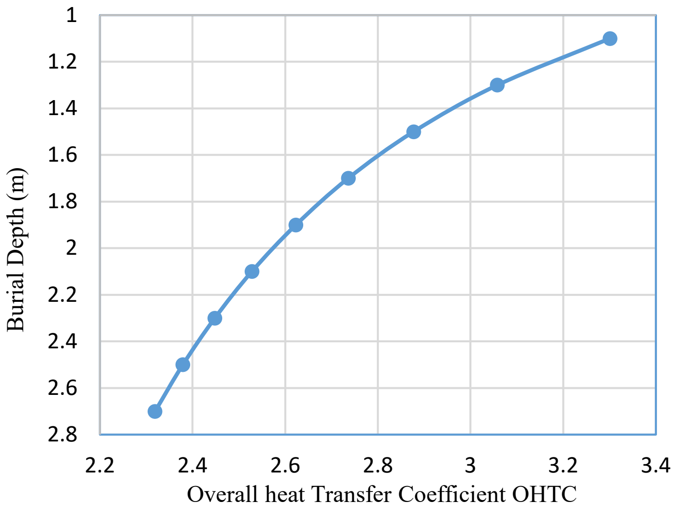

Figure 4: Shows burial depth vs OHTC

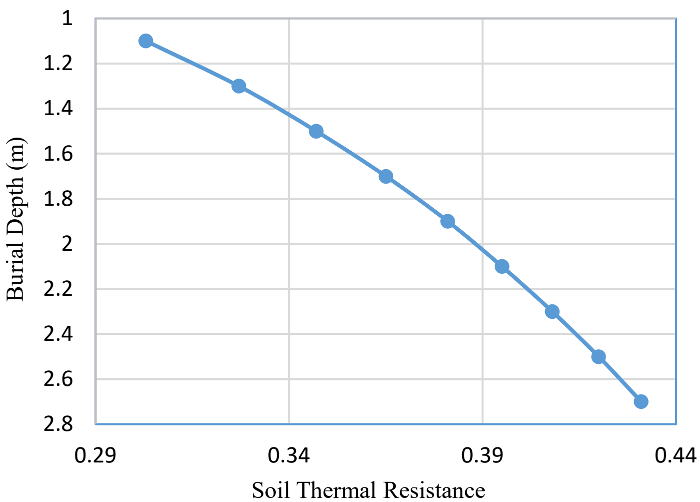

Figure 5: Shows burial depth vs Soil thermal resistance

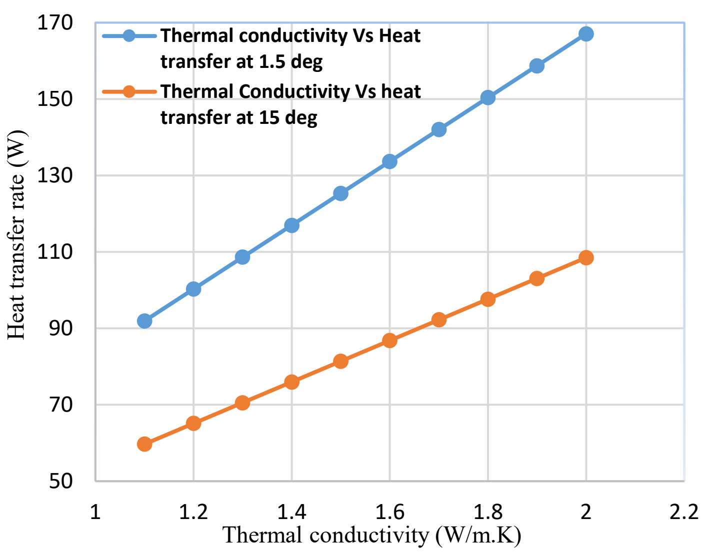

Figure 6: Shows plot of thermal Conductivity against Heat Transfer at 1.5°C and 15°C ambient temperature

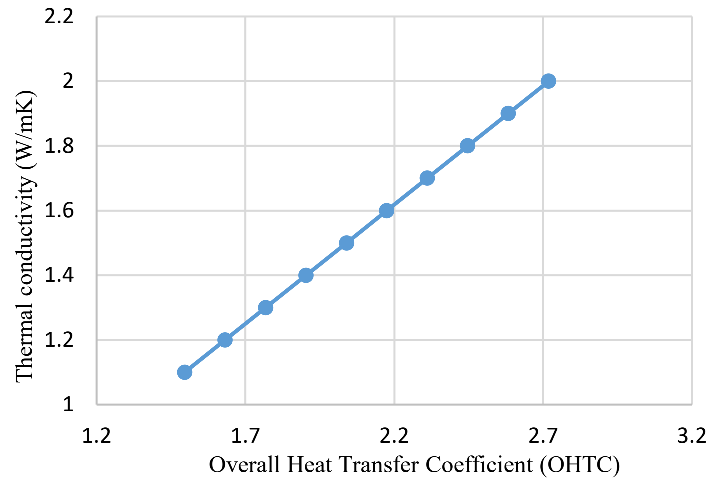

Figure 7: Shows Thermal conductivity vs OHTC

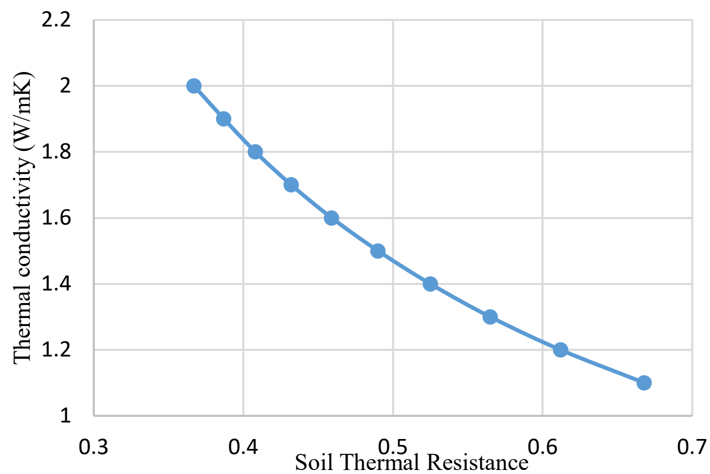

Figure 8: Shows Thermal conductivity vs Soil thermal resistance

4.2 Effects of Thermal conductivity

Pipeline and soil material properties such as thermal conductivity k, density ρ and specific heat capacity as presented in table 2 also play a key role in determining the temperature difference between the pipe and its surrounding. The thermal conductivity value of 1.8W/mK used for modelling was varied from 1.1-2.0W/mK and intervals of 0.1 to represent different soil thermal conductivity values. Figure 13 shows a plot of the varied thermal conductivity against pipeline burial depth against the corresponding heat transfer rate for both 1.5°C and 15°C ambient temperatures. From figure 6, the heat transfer rate also increases with increasing thermal conductivity and also doubles over the aforementioned range. A reduction in thermal conductivity of the soil also reduces the heat transfer rate and vice versa. The heat transfer rate also increases at higher ambient or surface temperature of 15°C when compared to low ambient or surface temperatures of 1.5°C. From figure 8, the thermal resistance of the soil reduces with increasing thermal conductivity while the OHTC increases with increasing thermal conductivity as shown in figure 7. The OHTC doubles over the range. However, the heat transfer rate remains constant with increasing mass flow rate. An increase in the flow rate of the pipeline also increases the Reynolds number, Nusselt number and the internal convection coefficient of the dense phase CO_2 in the pipeline.

5. CONCLUSION

A one-dimensional analytical model has been studied for the steady state heat transfer of buried pipeline for dense phase CO_2 onshore transportation for CCS. The effects of the pipeline burial depth and soil thermal conductivity on the pipeline heat loss, soil thermal resistance and ambient temperature have been investigated using the overall heat transfer coefficient approach, the electrical analogy of thermal resistance. It has been found that the heat transfer rate decreases laterally with increasing pipeline burial depth at higher ambient temperature while the heat transfer rate increases significantly at low ambient temperatures. Pipeline heat loss to the ambient surroundings has been calculated based on a one-dimensional shape factor model under steady-state conditions for buried pipes whilst assuming a constant temperature from the pipeline fluid. Consequently, with particular focus on the pipeline burial depth, i.e. the region between the pipeline center and the soil surface, results show that effects of convection heat transfer to the ambient air and soil surface cannot be ignored. It has been found that a reduction in the soil thermal conductivity subsequently reduces the heat transfer rate and vice versa. The heat transfer rate also increases at higher ambient or surface temperature of 15°C when compared to low ambient or surface temperatures of 1.5°C. From figure 8, the thermal resistance of the soil reduces with increasing thermal conductivity while the OHTC increases with increasing thermal conductivity. Design of buried onshore CO_2 giving particular considerations to the soil thermal conductivity and pipeline burial depth is significant to pipeline heat loss calculations during design and can go a long way in the mitigation of pipeline temperature and pressure drop that will in turn help reduce the formation of CO_2 hydrates and phase change in the dense phase or supercritical fluid in the pipeline.

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