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A Study on Heat Loss from Offshore Pipelines Depending on the Thermal Conductivity of Backfills and Burial Depth

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Abstract

Subsea pipelines are designed to transport mixtures of oil, gas, and their associated impurities from the well-head that can have temperatures as high as 100℃, while the external temperature can be as low as 5℃. Heat can be lost from the subsea pipeline containing high-temperature fluid to the surrounding environment. It is important that the pipeline is designed to ensure that the heat loss is small enough to maintain flow and avoid the unwanted deposition of hydrate and wax, which occurs at a critical temperature of approximately 40℃. Therefore, it is essential to know the heat loss of subsea pipelines under various circumstances. This paper presents a comparison between numerical analyses and existing theoretical formulas for different backfills and burial depth.

Keywords: Heat loss, Overall heat transfer coefficient, Backfill, Burial depth, Thermal conductivity, Numerical analysis

1. Introduction

As offshore plant industries are growing, the demand for subsea pipelines for the transport of crude and natural gas is increasing and thermal management issues during such transport are emerging as research topics. In the case of subsea pipelines, heat loss occurs to the oil and natural gas being transported at approximately 100°C because of cold seawater and seabed maintained at around 5°C. The operation of subsea pipelines is temporarily suspended when the temperature drops below 40°C(extreme temperature) owing to the generation of hydrates and wax, which causes significant economic loss. To prevent hydrates and wax from being generated, it is essential to identify the time period in which the crude and natural gas reach the extreme temperature. Since the time period varies depending on the pipe as well as the seabed around the pipe, backfill, and thermal conductivity of the seawater, it is necessary to understand their thermal properties (thermal conductivity and specific heat).

Various insulation methods have been researched and developed including pipe-in-pipe(PIP) systems, in which solid polypropylene, polypropylene foam, and polyurethane are applied in multiple layers to the outer wall of subsea pipelines, to prevent the generation of hydrates and wax. The economical and universal insulation method, however, is to bury the pipe in the seabed and cover it with backfill. Although previous studies on backfill used for onshore pipelines suggested the thermal resistance of the soil through various samples that used different particle-size distributions and water contents of the backfill, the backfill used for subsea pipelines is different in that it usually covers the soil of the ground formed around the pipe and thus,

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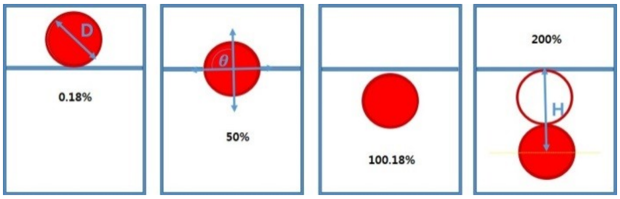

Fig. 1 Burial depth of a subsea pipeline

the relevant data are not sufficient.

In previous research, some theoretical formulas for calculation of OHTC(Overall heat transfer coefficient) have been suggested. In 1959, Carslaw&Jaeger(Carslaw and Jaeger, 1959) suggested OHTC formula assuming isothermal(Dirichlet) boundary condition at the interface of seabed, seawater and subsea pipe. After Carslaw&Jaeger formula, Morud&simonsen formula(Morud and Simonsen, 2007) and Ovuworie formula(Ovuworie, 2010) was suggested. These two formulas changed boundary condition of the interface of seabed, seawater and subsea pipe to convective(mixed) boundary condition. Recently, in 2012, Zakarian suggested OHTC formula cold OTC23033 formula(Zakarian et al., 2012). In this study, heat loss was numerically obtained according to the types of backfill suitable for the seabed, as well as the burial depth. Finally, the results were compared with Carlsaw&Jaeger formula and OTC23033 formula.

2. Theoretical Formulas for the Overall Heat Transfer Coefficient

2.1 Overall Heat Transfer Coefficient (OHTC)

Overall heat transfer coefficient(OHTC) of subsea pipeline is a measure of the overall ability of a series of conductive(Subsea pipe wall) and convective(Sea water and internal fluid) barriers to transfer heat. OHTC(U) can be expressed using equation (1) according to the burial depth shown in Fig. 1. In equation (1), $U_{unburied}$ is the OHTC when the pipe is completely exposed to the seawater. U_{ground} and U_{buried} are the overall heat transfer coefficients of the ground in the cases of $-\frac{D_0}{2} \leq H < \frac{D_0}{2}$ and $\frac{D_0}{2} \leq H$, respectively, as shown in equation (1). In this equations, D_o means outer diameter of pipe.

$$U = \begin{cases} \frac{\theta_b}{\pi} U_{unburied} + \left(1 - \frac{\theta_b}{\pi}\right) U_{ground} & if\ -\frac{D_0}{2} \leq H < \frac{D_0}{2} \\ U_{buried} & if\ \frac{D_0}{2} \leq H \end{cases} \tag{1}$$

Leading theoretical formulas that define the OHTC include Carslaw's and Jaeger's formula, Morud's and Simonsen's formula, Ovuworie's formula, and the OTC 23033 formula. In this study, the results of the numerical analysis were verified through a comparison with the OTC 23033 formula, which has some modifications compared with Carslaw's and Jaeger's formula and Ovuworie's formula.

2.2 Carslaw's and Jaeger's Formula

Carslaw's and Jaeger's formula assumes isothermal boundary conditions for the seawater, seabed, and outer surface of the pipe and defines the OHTC based on the heat transfer coefficient $h_{soil+amb}$. In equation (2), D_i means inner diameter of pipe, k means thermal conductivity and h_i means internal heat transfer coefficient.

$$U_{ground} = \left(\frac{D_0}{D_i h_i} + \frac{D_0 \ln(D_0/D_i)}{2k_{pipe}} + \frac{1}{h_{soil+amb}}\right)^{-1} \quad U_{buried} = \left(\frac{D_0}{D_i h_i} + \frac{D_0 \ln(D_0/D_i)}{2k_{pipe}} + \frac{1}{h^*_{soil+amb}}\right)^{-1} \tag{2}$$

The heat transfer coefficients $h_{soil+amb}$ and $h^*_{soil+amb}$ in equation (2) are defined as follows.

$$h_{soil+amb} = \frac{k_{soil}}{\frac{D_0}{2}\cosh^{-1}\left(1+\frac{2e}{D_o}\right)} \qquad h^{*}_{soil+amb} = \frac{k_{soil}}{\frac{D_0}{2}\cosh^{-1}\left(\frac{2(H+e^{*})}{D_o}\right)} \tag{3}$$

The Parameters, e and e^{*}, in equation (3) are defined as shown in equation (4).

$$e = \frac{D_0}{2}\left[exp\left(\frac{2k_{soil}}{D_0 h_0}\right) - 1\right] \qquad e^{*} = \frac{D_{soil}}{2}\left[exp\left(\frac{2k_{soil}}{D_{soil} h_{amb}}\right) - 1\right] \tag{4}$$

D_{soil} represents the influence diameter of the soil related to h_{soil}. The external film heat transfer coefficient, h_{amb}, can be obtained using the external convective heat transfer coefficient, h_o, as shown in equation (5).

$$h_{amb} = \frac{D_0}{D_{soil}} h_o \tag{5}$$

2.3 OTC 23033 (Zakarian) Formula

The OTC 23033 formula contains some modifications to Ovuworie's formula, as shown in equation (6). The internal film heat transfer coefficient and the heat transfer coefficient of the pipe wall were removed from the U_{buried} term.

$$\begin{aligned} U_{ground} &= \left(\frac{D_0}{Dih_i} + \frac{D_0 \ln(D_0/D_i)}{2k_{pipe}} + \frac{1}{h_{ground}} + \frac{1}{h_{amb}}\right)^{-1} \\ U_{buried} &= \left(\frac{D_0}{Dih_i} + \frac{D_0 \ln(D_0/D_i)}{2k_{pipe}} + \frac{1}{h_{buried}} + \frac{1}{h_{amb}}\right)^{-1} \end{aligned} \tag{6}$$

The heat transfer coefficients, h_{ground} and h_{buried}, can be obtained by combining the internal film heat transfer coefficient, the heat transfer coefficient of the pipe wall, and the heat transfer coefficient of the backfill as shown in equation (7).

$$\begin{aligned} h_{ground} &= \frac{2k_{soil}}{D_0} \frac{Bi_p}{\left[\left(1+\frac{Bi_p}{Bi_g}\right)(1+2Bi_p)\right]^{1/2}} \\ h_{buried} &= \frac{2k_{soil}}{D_0} \frac{Bi_p \sinh(\alpha_0)}{\left[\left(\cosh(\alpha_0)+Bi_p\alpha_0 \sinh(\alpha_0)+\frac{Bi_p}{Bi_g}\right)^2 - \left(1+\frac{Bi_p}{Bi_g}\right)^2\right]^{1/2}} \end{aligned} \tag{7}$$

In addition, the Biot number (Bi_p), which indicates the temperature drop between the surface and the interior of an object, and α_0, which is a function of the burial depth in equation (7), can be expressed as shown in equation (8).

$$Bi_p = \frac{U_{i+wall} D_0}{2k_{soil}} \qquad Bi_g = \frac{h_{amb} D_0}{2k_{soil}} \qquad \alpha_0 = \cosh^{-1}\left(\frac{2H}{D_0}\right) \tag{8}$$

The heat transfer coefficient, U_{i+wall}, can be derived from the combination of the internal film heat transfer coefficient and the heat transfer coefficient of the pipe wall as shown in equation (9).

$$U_{i+wall} = \left(\frac{D_0}{D_i h_i} + \frac{D_0 \ln(D_0/D_i)}{2k_{pipe}}\right)^{-1} \tag{9}$$

The external film heat transfer coefficient in equation (6), h_{amb}, can be obtained using h_o as shown in equation (10).

$$h_{amb} = \frac{D_0}{D_0} h_o = h_o \tag{10}$$

3. CFD Analysis of the Overall Heat Transfer Coefficient

In this study, ANSYS CFX v13.0, a commercial numerical analysis program with proven accuracy of heat transfer analysis, was used as a comparative study(Papukchiev and Buchholz, 2017). In the numerical analysis, The OHTC is calculated by using the mean temperature of the outlet, inlet and surface of the subsea pipe when the temperature of the whole model reaches the steady state by certain temperature(70℃) of internal fluid. And compared with the theoretical formulas.

3.1 Modeling and Grid Creation

In the numerical analysis, the grid dependence disappears at the number of nodes at fifteen million and set. Based on the created grids, the well-known commercial code ANSYS CFX v.13 was used to set boundary conditions and conduct a CFD analysis. The numerical analysis was conducted using a three-dimensional model, in which the outer diameter and thickness of the pipe were 55mm and 2mm, respectively, while the burial depth of the pipe was varied as 200%, 100.18%, 80%, 60%, 40%, and 20%(Oh et al., 2014). The burial depth is defined using equation (11).

$$\textit{Burial depth (\%)} = \left(\frac{H}{D_0} + \frac{1}{2}\right) \times 100 \tag{11}$$

3.2 Boundary Conditions

The types of backfill soil were classified using the unified soil classification system into gravel, sand, and clay, which had different particle-size distributions. In addition, the numerical analysis was conducted using thermal conductivity, specific heat, and density when the water content of each sample was 40%(Cha et al., 2008; Bai and Bai, 2005; Farouki, 1981). In the initial condition, the temperatures of the seawater, seabed, pipe, and fluid in the pipe were set to 0℃. The seabed and the wall of the seawater were set to wall boundary condition and their temperatures were set to 0℃. It was assumed that the seawater had a laminar flow while the fluid transported inside the pipe had a turbulent flow. The flow velocity of the seawater was set to 0.05m/s. OHTC was obtained two cases. One case are obtained when the temperature of the pipe wall reached the steady state under the condition that the temperature and flow velocity of the fluid inside the pipe were 70℃ and 0.4095m/s, respectively. And the other cases obtain without internal convection but boundary condition of same temperature of inner pipe wall.

4. Analysis Results of the Overall Heat Transfer Coefficient

4.1 Theoretical Formulas and Results of the Numerical Analysis

The test was conducted using a pipe model without insulating materials. The heat transfer coefficient of the pipe wall (U_{wall}) of a pipe without insulating materials is higher than that of a pipe coated with insulating materials. The heat transfer coefficient of the pipe wall in the model was 14,447.68W/m^2℃. In addition, the Biot number (Bi_p) increased to 783.188, 445.4412, and 407.0812 in clay, sand, and gravel, respectively. In the case of the internal film heat transfer coefficient of the pipe wall (h_i), the value of the CFX was ten times higher or more than those obtained using theoretical formulas. Because the heat transfers to the outside of the pipe is more influential than the heat transfer inside the pipe, this study conducted an analysis excluding the internal film heat transfer coefficient.

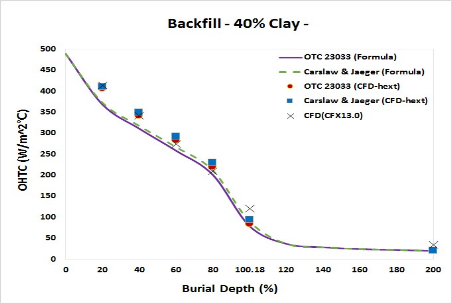

Fig. 2 Comparison of OHTC at clay backfill with different burial depth without internal convection

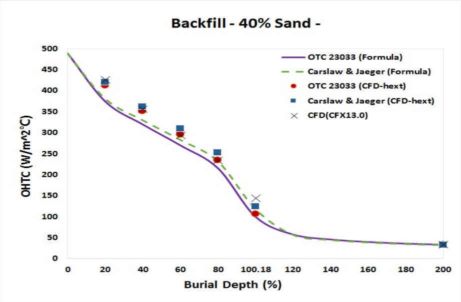

Fig. 3 Comparison of OHTC at sand backfill with different burial depth without internal convection

In that case, the internal wall of the pipe was maintained at 70℃. Figs. 2, 3, and 4 show the results when respectively, clay, sand, and gravel with a water content of 40% were used as backfill soil. The results of the CFD analysis were compared with those of Carslaw's and Jaeger's formula and the OTC 23033 formula. The results of the numerical analysis showed that the OHTC decreased as the burial depth increased. Furthermore, it was found that the coefficient sharply decreased for burial depth between 0% and 100.18%, but slowly decreased for burial depth between 100.18% and 200%. The thermal conductivity of clay is lower than those of sand and gravel, and it was confirmed that the backfill soil with a lower thermal conductivity produces higher insulation effects, as shown in Fig. 5.

4.2 Errors of the Formulas and Numerical Analysis

Fig. 6 compares the results in Fig. 2. It shows the errors between the OHTC obtained by applying the value of $\mathrm{h}_{\mathrm{ext}}$ derived using the numerical analysis and using Carslaw's and Jaeger's formula and the OTC 23033 formula. The errors tended to decrease as the burial depth increased for both formulas. The average errors were slightly below 9%. Fig. 7 also shows the accuracy of the results in Fig. 2. It shows the accuracy of the OHTC derived by CFD (CFX 13.0) by comparing it with the OHTC obtained by Carslaw's and Jaeger's formula and the OTC 23033 formula. As in Fig. 6, the errors decreased with the increase of burial depth but the rate of decrease rapidly declined compared with Fig. 6. Furthermore, the errors at a burial depth of 80% were much lower than those at a burial depth of 20%.

5. Conclusion

In this study, the OHTC was calculated using the existing formulas as well as numerical analysis and the results were compared to investigate the heat loss of subsea pipelines according to the types and depth of backfill soil. It was found that the OHTC increased with the use of clay, sand, and gravel with water contents of 40%. This indicates that clay with a low thermal conductivity may reduce the heat loss of subsea pipelines while gravel with a high thermal conductivity is relatively vulnerable to heat loss. In addition, heat loss decreased as the burial depth increased. OHTC tended to sharply decrease for pipe burial depth between 0% and approximately 100% but slowly decreased for burial depth between 100% and 200%. The results of this study can be used to economically fabricate or design insulating materials as well as burial depth because it is possible to estimate the heat loss of subsea pipelines caused by the seabed of the construction site during the design and construction of the pipelines. In the future, it is necessary to conduct research on the cooling time of the fluid inside the pipe according to the backfill soil types and the burial depth in case of a shutdown, in order to increase the economic efficiency and stability in terms of the design and fabrication of subsea pipelines.

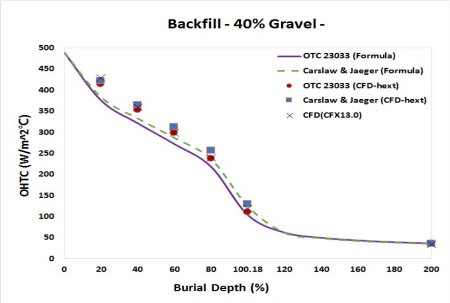

Fig. 4 Comparison of OHTC at gravel backfill with different burial depth without internal convection

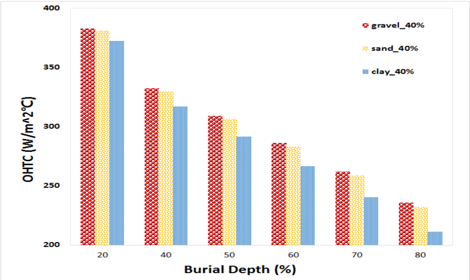

Fig. 5 Comparison of OHTC at various backfills with different burial depths without internal convection

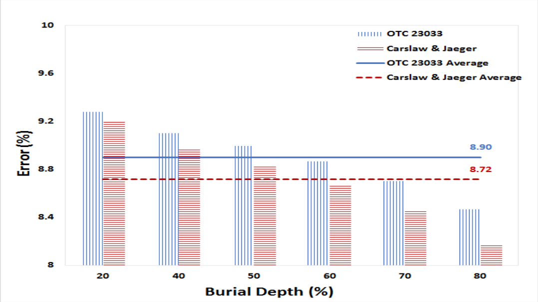

Fig. 6 Accuracy of (CFD-$h_{(ext)}$) results by burial depth

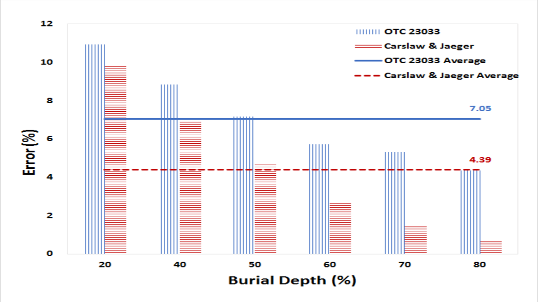

Fig. 7 Accuracy of CFD (CFX 13.0) results by burial depth

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