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Modeling deepwater seabed steady-state thermal fields around buried pipeline including trenching and backfill effects

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ABSTRACT

Deepwater pipelines are designed to transport mixtures of oil and gas, and their associated impurities at wellhead temperatures that can be in excess of 149 °C (~300 °F or 422 K) while the external temperature maybe in the range of 5 °C (~41 °F or 278 K). Depending on the circumstances these pipelines may be buried for physical protection or for additional thermal insulation using robotic trenching equipment. This results in a complex cut and backfill geometry in the seafloor in addition to altering the thermal properties of the backfill. A two-dimensional boundary element model was developed specifically to address to investigate the local steady-state thermal field in the near field of the pipeline. The model allows one to account for the complex geometries in the near field associated with this burial technique, site-specific multi-layered soil conditions and the seawater adjacent to the seafloor. A parametric study was preformed to evaluate effects of the thermal power loss, burial depth, pipe diameter and soil thermal conductivity on the thermal field in the near field of a buried pipeline. The numerical examples illustrate the influence of the backfill thermal property on the temperature at the pipe wall, that the pipe diameter controls the required output thermal power needed to maintain the desired pipe wall temperature, and the importance of pipeline burial depth on seabed temperature distribution above the pipeline.

1. Introduction

The low ambient temperature observed in very deepwater and at Arctic sites has led to innovative pipeline designs to assure the transport oil produced in these regions. As a consequence of the heat dissipation rates from pipelines transporting very hot multiphase wellhead fluids to the surrounding environment, thermal insulation may be complimented with integrated heating systems in order to mitigate possible flow assurance issues. Both passive and active thermal designs such as thermal insulation, pipe-in-pipe systems and direct electrical heating techniques [1] have been used in order to adequately maintain the temperature of hydrocarbons being transported. For long pipelines seafloor burial reduces the upheaval risk resulting from axial thermal expansion [2], and provides a cost effective thermal insulation when compared to pipe-in-pipe thermally insulated systems [3]. Heggdal et al. [4] investigated the use of direct electrical heating for large diameter deepwater subsea pipelines. In some situations heating systems are introduced to reduce the viscosity of crude oil, and prevent hydrate formation or wax deposition in the pipelines. Though most pipelines with active electrical heating or pipe-in-pipe heating system designs typically remain on the seafloor, burial may needed in regions where iceberg scouring of the seabed is expected. The major concerns when using the heating technology include the potential for aggravating thermal buckling problem due to overheating and the unintended consequences of the heat dissipated from these pipelines that may adversely affect the local marine environment and ecosystem. Burial of these subsea pipelines as they approach coastal waters can also provide a degree of protection from accidental damage due to entanglement of fishing gear, anchoring of ships or other floating platforms.

Earlier research studies by [5,6]; and Bau [7] developed an analytical approach to study the thermal behavior of a buried pipe and the surrounding soil. For cases where one wishes to investigate the spatially dependent thermal properties or piecewise homogeneous domains, numerical simulations and/or experimental investigations must be pursued in order to more accurately characterize the resulting thermal distributions. Representative studies investigating buried pipelines and power cables using a variety of numerical methods are summarized in Table 1. The thermal field in soil

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Table 1
Methodology comparison of heat transfer analysis of buried power cables and pipelines.

Year	Author	Time dependence	Numerical scheme	Property of soil	Dim.	Operational mode	Comment
1979	Mitchell	Transient and steady	FEM	Homogeneous mother soil	2D	Operational mode of power cables	Convection of air was included. Geometry of trench, thermal property of soil, cable size, and solar radiation were included. Geometry of cable was not kept. Natural convection in soil was not considered. Time consuming on modeling and computation
1988	Gela	Steady state	BEM	Homogeneous mother soil	2D	Operational mode of power cables	Convection of air was neglected. Trenching and backfill were considered. Natural convection in soil was not included. Both single cable and multi-cable system were studied. It is efficient on modeling and computation
1993	Hanna	Transient	FDM	Homogeneous mother soil	2D	Operational mode of power cables	Convection of air was handled. Trenching and backfill effect were included. Geometry of cable was not kept. It didn't include natural convection.
2008	Lu	Transient	FVM	Homogeneous and porous	2D	Shut down of oil pipelines	Convection of air was included. Natural convection in soil and conduction between cooling oil and pipe wall were treated. Trenching and backfill were not handled
2008	Barletta	Transient	FEM	homogeneous	2D	Start-up of oil pipelines	Natural convection was not comprised. Conduction and convection on seabed were not included. Trenching and backfill were not considered
2010	Xu	Transient	FVM	Homogeneous	2D	Shut down of oil pipelines	Equivalent conductivity was adopted to simplify convection between oil and pipe wall. Convection of air was handled. Natural convection in soil and trenching effect were not included

near power cables placed in a trench was investigated by Mitchell and Adel-Hadi [8], Gela and Dai [9,10]; and collectively these studies provide a guide for the design of sheathing for power cables. In those studies the soil was modeled as a solid media, and it was determined that critical parameters affecting the heat dissipation in the soil included the thermal property of backfill material, the burial depth, and layout of the cables. Neglecting trenching and backfill, Lu et al. [11] used their model to investigate the phase change phenomenon of fully saturated soils around a buried pipe in winter conditions. They investigated the heat conduction effects of crude oil in the pipeline and the natural convection of fluid flow induced in the soil during a shutdown period. Assuming soil to be a homogeneous solid media, Barletta et al. [12] studied the temperature fluctuation in a subsea pipeline under the start-up and shutdown conditions using a finite element model. Later Xu et al. [13] used a finite volume method to investigate the shutdown time neglecting both the convection of fluid flow in soil and the backfill conditions. In an experimental study Newson et al. [14] investigated the influence of moisture and void ratio changes on the thermal conductivity of seabed clay in the North Sea. They found that the moisture content of disturbed clay could be up to 95% and that the corresponding thermal conductivities decreased to 0.8 W/m K, which approaches that of still seawater 0.65 W/m K. In the contrast, the thermal conductivity of the undisturbed clay is typically around 1.0 W/m K. Based upon numerical simulations using Code_Bright [17], it was determined that for the extremely low hydraulic permeability 10^{-8}–10^{-7} m/s associated with deepwater clay that the natural convection resulting from the heat exchange with the pipeline controls the time required to reach the steady state but not the final steady state temperature distribution.

In earlier studies the boundary element method (BEM) has been shown to be a very efficient approach for modeling multiple domains to solve both two-dimensional steady state [15] and three-dimensional static elastic problems [16]. For this research investigation a two-dimensional (2-D) boundary element formulation utilizing quadratic boundary elements is developed to specifically investigate the steady state thermal field around a buried pipeline. This approach was selected for its ability to effectively model complex geometries associated with the inclusion of trenching and backfill in a layered seafloor resulting from pipeline burial. The boundary element model as presented is used to investigate sensitivity of the steady state thermal field as influenced by the pipeline burial depth, the pipe diameter and the thermal conductivity of backfill material.

2. Mathematical formulation

Osborne et al. [18] describe the complete process of pipeline burial in deepwater using a remotely operated vehicle (ROV). A two-dimensional vertical slice of the irregular sub-seafloor geometry that typically results from the trenching and backfilling process by the ROV is illustrated in Fig. 1.

The model involves four domains, two layers of undisturbed soil a third containing the backfill material and the fourth containing seawater. In the model the domain containing seawater adjacent to the seafloor, the fluid is assumed to be a hydraulically quiescent layer where the inclusion of seawater convection initiated in the seabed is neglected. The problem variables used in the formulation of the boundary element model are presented in Fig. 1. The variables Ω_1, Ω_2, Ω_3 and Ω_4 denote the sub-layer soil, the top layer soil, the backfill region, and the seawater domains respectively. The variables Γ_1, Γ_2, Γ_3 and Γ_4 are used to represent the domain boundaries for their respective domains. The geometric parameters defining vertical dimensions of the problem domain are D_1, D_2, and D_4 and the horizontal width of the domains is denoted as L. The cover depth of pipeline is D_b, the dimension at the lower section

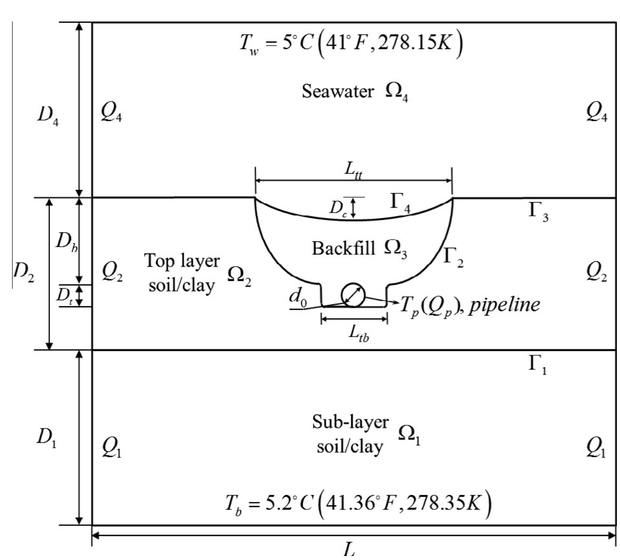

Fig. 1. Sketch of the pipe-trench model for heat transfer analysis.