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Numerical study of heat transfer from an offshore buried pipeline under steady-periodic thermal boundary conditions

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Abstract

The steady-periodic heat transfer between offshore buried pipelines for the transport of hydrocarbons and their environment is investigated. This heat transfer regime occurs for shallow water buried pipelines, as a consequence of the temperature changes of the seabed during the year. First, the unsteady two dimensional conduction problem is written in a dimensionless form; then, it is transformed into a steady two dimensional problem and solved numerically by means of the finite–element software package Comsol Multiphysics (© Comsol, Inc.). Several values of the burying depth and of the radius of the pipeline, as well as of the thermal properties of the soil are considered. The numerical results are compared with those obtainable by means of an approximate method employed in industrial design. The comparison reveals that important discrepancies with respect to this approximate method may occur.

Keywords: Offshore buried pipelines; Heat transfer; Steady-periodic boundary conditions; Numerical methods; Industrial design

1. Introduction

As is well known, offshore buried pipelines are often used for the transport of hydrocarbons from extraction sites to refinement plants. The design of these pipelines requires the knowledge of the overall heat transfer coefficient from the pipe wall to the environment. In fact, a significant decrease of the fluid temperature could cause the formation of hydrates and waxes which might stop the fluid flow. Moreover, the knowledge of the bulk temperature of the fluid in any cross section is necessary to determine the value of the fluid viscosity in that section and, thus, to evaluate the viscous pressure drop along the flow direction. As a consequence, the heat transfer from buried pipelines has been widely studied in the literature [1–4]. An analytical expression of the steady-state heat transfer coefficient from an offshore buried pipeline to its environment can be found in [5]. It refers to the boundary condition of a uniform temperature of the seabed, i.e. of the separation surface between soil and sea water. In these conditions, the thermal power exchanged between the pipeline and its environment, per unit length of the duct, can be expressed as

$$\dot{Q} = k(T_a - T_e)\Lambda_0, \tag{1}$$

where k is the thermal conductivity of the soil, T_a is the temperature of the external surface of the duct, T_e is the temperature of the seabed and Λ_0 is a dimensionless heat transfer coefficient, given by

$$\Lambda_0(\sigma) = \frac{2\pi}{\operatorname{arccosh}(\sigma)}. \tag{2}$$

In Eq. (2), σ is the ratio between the burying depth of the pipe axis, H, and the external radius of the pipe, R.

Eqs. (1) and (2) provide reliable results in many cases, but cannot be applied, for instance, in the following

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Nomenclature

A, B	dimensionless coefficients
a	dimensionless length
C	dimensionless constant defined in Eq. (A.2)
c_v	soil specific heat at constant volume
H	burying depth of the pipeline
k	soil conductivity
$\vec{n}$	normal unit vector
q	thermal power per unit area
$\dot{Q}$	thermal power per unit length
$\dot{Q}_{const}$	thermal power per unit length, in the constant power limit
$\dot{Q}_{qs}$	thermal power per unit length, in the quasi-stationary limit
R	pipeline radius
T_a	pipeline wall temperature
T_e	seabed temperature
T_{eff}	effective temperature
T_H	soil temperature at a depth H
T_m	mean annual seabed temperature
T_0, T_1, T_2	temperature fields
t	time
X, Y	coordinates
x, y	dimensionless coordinates

Greek symbols

α	soil thermal diffusivity
β, γ	dimensionless quantities defined in Eq. (A.4)
ΔT	amplitude of temperature oscillations
$\theta_0, \theta_1, \theta_2$	dimensionless temperature fields
Λ_0	dimensionless heat transfer coefficient
Ξ	dimensionless parameter
ρ	soil density
σ	dimensionless burying depth
Σ	dimensionless parameter
ϕ	phase angle defined in Eq. (A.3)
ω	angular frequency

Superscripts, subscripts

*	dimensionless quantity
max	maximum value
min	minimum value

circumstance. For shallow–water pipelines, the temperature of the seabed is affected by the season changes and varies accordingly during the year. With reference to the Mediterranean sea, the seabed statistically reaches a minimum value of 14 °C, in winter, and a maximum value of 25 °C, in summer. Clearly, this temperature change of the seabed may have a strong influence on the thermal power exchanged between the pipeline and its environment.

At present, an approximate method is employed in industrial design to take into account this effect. The soil is considered as a semi–infinite solid medium whose surface temperature varies in time according to the law

$$T = T_m + \Delta T \sin(\omega t), \tag{3}$$

where T_m is the mean annual temperature of the seabed, ΔT is the amplitude of the temperature oscillation and ω is the angular frequency which corresponds to the period of one year, namely

$$\omega = 0.1991 \times 10^{-6}\,\mathrm{s}^{-1}. \tag{4}$$

Thus, by assuming that the pipeline does not modify considerably the temperature distribution in the soil, at a depth H one has [6]

$$T_H = T_m - \Delta T \exp\left(-\sqrt{\frac{\omega}{2\alpha}}\,H\right) \sin\left(\sqrt{\frac{\omega}{2\alpha}}\,H - \omega t\right), \tag{5}$$

where α is the thermal diffusivity of the soil. In the approximate method, the thermal power is evaluated as

$$\dot{Q} = k(T_a - T_H)\Lambda_0, \tag{6}$$

i.e. by replacing T_e with T_H in Eq. (1).

The approximate method does not seem reliable because it is not based on a rigorous mathematical model. To check the reliability of the method, one can apply it to evaluate the heat transfer between a plane isothermal surface buried at a depth H and the surrounding soil, when the temperature of the ground surface varies in time according to Eq. (3). In fact, for this case, an analytical expression of the soil temperature field is available in the literature [7]. This analysis has been performed with reference to standard properties of the soil and is reported in Appendix A. The comparison between the analytical solution and the approximate method shows that the latter yields acceptable results only when very small values of H are considered. Therefore, a more reliable method to evaluate the steady-periodic heat transfer from buried pipelines to the environment is needed.

The aim of this investigation is to find out an accurate method to determine the heat transfer between an offshore buried pipeline and its environment in steady-periodic conditions. First, by introducing suitable auxiliary variables, the unsteady two dimensional conduction problem is transformed into a steady two dimensional problem in the new variables. Then, the steady problem is solved numerically by means of the software package Comsol Multiphysics (©Comsol, Inc.). The results show that the empirical method given by Eqs. (6), (5) and (2) may yield a too rough approximation in some cases.

2. Mathematical model

Let us assume that the temperature of the seabed varies in time according to Eqs. (3) and (4). The computational