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Study of Soil Heat Transfer of a Natural Gas Pipeline

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The heat transfer between the pipeline fluid and the ambient is important to accurately model the flow. In this study, the modelled transient thermal regime in the soil around the pipeline is compared to the measurements. The thermal and hydraulic properties of the soil were determined through experimental methods and predictive modelling. The contribution of natural convection from ground water was assessed through the model and subsequently lifted to the general case of a buried pipeline through the use of nondimensional numbers. The results show that a numerical calculation model using only heat conduction can represent the soil temperatures accurately and at larger distances from the pipe wall. The results show that using predictive modelling to determine the thermal properties of the model is a valid approach compared to soil sample or in situ measurements. The role ground water plays in both forced and natural convection was demonstrated and found to be of minor significance for the studied case.

INTRODUCTION

Models used to monitor and control gas pipelines depend on the accurate calculation of the gas temperature, pressure, and flow rate. The representation of the thermal exchange with the ambient influences aspects of the pipeline operation such as the inventory control, leak detection, and avoidance of overpressurization. Gas pipe flow models are usually approximated by 1D discretization of the Navier Stokes equations, describing the nonisothermal, compressible turbulent flow.

In modelling the pipe flow, the heat transfer between the gas in the pipeline and the surrounding soil plays a significant role, particularly during the transient flow. Usually an external heat transfer model is coupled to the energy equation of the flow. Different modelling approaches for the external heat transfer model are discussed in Modisette (2002). The choice of this model has a significant impact on the calculation of the pipe fluid hydraulic parameters, as demonstrated in Chaczykowski (2010), Helgaker et al. (2013), Oosterkamp et al. (2014), and Sund et al. (2015).

Often, the large length of a gas pipeline, combined with the need for the real-time calculation of the flow parameters, puts restrictions on the complexity of an external heat transfer model. Often, the external heat transfer models are limited to a steady-state representation of heat conduction using an overall heat transfer coefficient that combines the inner-film heat transfer coefficient from the gas to the pipe wall, the thermal resistance of the pipe wall layers, and the 2D soil domain (Archer and O'Sullivan, 1997).

When the transient ambient heat transfer is included in the operational flow models, it is often based on the 1D radial unsteady heat conduction equation (Chaczykowski, 2010). The use of a two-dimensional (2D slices of soil at regular intervals along the pipeline route) or a three-dimensional representation of the pipe wall and soil is usually limited to dedicated studies of shorter pipeline sections. Typical assumptions for the external heat transfer model are that heat transfer through the pipe wall and soil layer can be described through the use of the 1D radial heat conduction equation and that thermal properties are constant in time.

Notable exceptions to the assumption that heat transfer can be solely represented by Fourier heat conduction are studies of the effects of the freezing/thawing of soil around the pipeline. Another example is the ground moisture transfer affecting thermal heating systems. The freezing and thawing of the moisture in the soil are thus recognized as important factors in the prediction of soil temperatures and are given considerable attention in the literature. The behavior of a liquid soil moisture phase in the presence of frozen soils and ice lenses is discussed in Harlan (1973), Jame and Norum (1980), and subsequent publications such as Song (2006), Kurylyk and Watanabe (2013), Gan (2013), Xu and Spitler (2014), Vitel et al. (2015), and Yang et al. (2015). In this work, the freezing/thawing of the soil has not been considered.

The problem of thermally-induced water movement in soils is discussed in Liu et al. (2013). Many soil properties are influenced by the thermal field and should be considered to be coupled to the hydraulic field. The heat transfer may change due to water migration, and the thermal properties of the soil can change. In the literature, several models can be found describing heat transfer and moisture migration in unsaturated soil.

The hydraulic migration of water in unsaturated soils can be described from thermodynamics in the Philip and de Vries model (Philip and de Vries, 1957). This model is derived from Darcy's law. The pressure differential is dependent on the gravitational and matric potential, the latter being a function of the surface tension of the temperature-dependent water-water vapor interface and the volumetric water content.

In Liu et al. (2013), the total potential is expanded with the osmotic envelope and the pneumatic potential. Further development entails three-phase porous media models that incorporate ice, water, and vapor phases. As shown in Xu and Spitler (2014), the unsaturated water flow in a porous media can be described by the modified Richards equation. The water flow is assumed to have two different flows caused by five separate processes. The liquid flow is caused by hydraulic-gradient-driven isothermal liquid diffusivity, thermal-gradient-driven liquid diffusivity, and gravity. The vapor flow is driven by hydraulic-gradient-driven isothermal vapor diffusion and temperature-gradient-driven vapor diffusion.

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