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Research Paper

Effect of the choice of boundary conditions on modelling ambient to soil heat transfer near a buried pipeline

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HIGHLIGHTS

- Study of the effect of surface boundary conditions on soil heat conduction models.
- The modelled results are compared to the experimental data of a buried pipeline case.
- Comparison of soil temperature profiles and pipe to ambient heat transfer.
- Accuracy is reduced when using measured air temperatures as the soil surface boundary.
- Best accuracy with real soil surface temperatures or full surface energy balance.

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ABSTRACT

The soil temperature distribution influences the thermal interaction between the ambient and subsurface objects. This paper shows the effect of the soil surface boundary conditions on heat transfer calculations around a buried pipeline. The results are compared to measurements from an experimental installation. Measurements include soil temperatures, the soil surface radiation balance, and weather parameters. The heat conduction problem is modelled with one- and two-dimensional models. The models were used to find the sensitivity for different soil surface boundary condition assumptions. The results are compared to the measured soil thermal profiles and the pipeline to ambient heat transfer. Using both the measured soil surface temperature and the full surface energy balance provides similar and accurate soil temperature prediction. A reduction in predictive accuracy of soil temperatures occurs when using measured air temperatures for the soil surface boundary condition This has an effect on the long term pipeline to ambient heat transfer.

1. Introduction

The heat transfer between the fluid in a gas pipeline and the environment is an influencing factor on the calculation of gas pressures, temperatures, and mass flow rate. To describe the soil surface boundary of a heat transfer model properly, the full surface energy balance needs to be used. Important aspects include solar, atmospheric, soil surface radiation, and convection heat transfer to the air surface layer. The migration of moisture into and out of the soil due to precipitation, condensation, and evaporation is an additional factor needed to describe fully the heat transfer problem. Due to the large length of export gas pipelines, the external ambient heat transfer model is desired to be as simple as possible in pipe flow calculations. The heat transfer problem of a buried gas pipeline is described in detail in Archer and O'Sullivan [1], Bau [2], and Sund et al. [3].

Typically, the models are limited to steady state conduction. In such models, the two-dimensional aspect of heat transfer of a buried pipe is made one-dimensional by using a steady state conduction shape factor, as shown in Incropera and DeWitt [4]. The heat transfer from the gas to the ambient is captured in an overall heat transfer coefficient, U, coupling the ambient heat transfer to the energy equation governing the pipe flow. This overall heat transfer coefficient combines the convective heat transfer from gas to pipe wall and the thermal resistance of the pipe wall layers and the soil. In Bau [5], the steady state one dimensional(1D) heat transfer model is extended to include convective heat transfer due to soil moisture migration around the pipe. Non-steady heat transfer models are normally restricted to 1D radial heat conduction, as described in Chaczykowski [6], Nicholas [7], and Helgaker et al. [8]. The use of two dimensional (2D) heat transfer models in connection with pipe flow is discussed in Oosterkamp et al. [9] and Yu et al. [10]. The effect upon calculated gas pressures and temperatures of the heat transfer model is described in detail in the above mentioned publications and an overview is provided in Sund et al. [3].

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In all these models, the detailed aspects of the ambient to soil energy balance are ignored. The heat transfer models used in modelling gas pipe flow used simplified boundary conditions. The full surface energy balance is not considered; it is not practical to measure this everywhere along the land-based sections of a pipeline route. Detailed knowledge of the soil surface temperatures above the buried pipeline is usually not available either. In the heat transfer models it is common practice that the soil surface temperature is either set equal to the air temperature or through a convective boundary condition. The air temperatures along the pipeline route are normally not measured directly. These are often obtained from a nearby meteorological station or derived from historical weather data. There is limited information available in the literature on the effect of the simplifications of the external heat transfer models as used in the flow modelling of gas and oil pipelines. In for example Yu et al. [10], an unsteady 2D heat transfer model is coupled to the flow equations of pipe flow in an oil pipeline. The model uses a convective boundary condition at the soil surface, with the air temperature approximated by a sine function of time. The analysis focuses on the boundary conditions at the pipe wall and the numerical methods that are employed to solve the heat transfer problem.

The problem of heat transfer of a buried gas pipeline has analogies with that of underground heat exchangers. In the literature, several publications can be found dealing with the effect of the model assumptions. In Florides and Kalogiru [11], a review of heat transfer models for ground heat exchangers is provided, discussing 1D, 2D and 3D heat transfer models. Some of these include the effect of soil moisture migration. The effect of the boundary conditions is given little attention. In Ozgener et al. [12] measured air temperature is used together with the analytical solution of one dimensional heat conduction (Hillel [13]) to predict the subsurface soil temperatures. The amplitude and phase shift of the annual soil surface temperature is approximated by fitting a sine with a one-year period to the air temperature data. Comparison with measured soil temperatures at 5, 10, 20 and 300 cm depth leads to maximum soil temperature errors as large as 6 K in the upper soil layer. The effect of the boundary condition on the resulting heat transfer rates is not reported but the notion is made that for more accurate calculations the soil surface temperature should be used.

In Liu et al. [14], a 1D radial unsteady model is used to model heat transfer between soil and flowing air in an underground tunnel. In this case, the outer boundary condition is considered to have constant temperature for a soil radius exceeding 10 m. The rationale provided here is that at depths of more than 10 m, the periodic variation of the air temperature does not affect the resulting heat transfer with the air inside the tunnel. The outer node of the soil model is set at the value of the undisturbed soil temperature at the corresponding depth. This concept is further explained in Krarti and Kreider [15].

Analytical solutions exist for the soil temperature profiles through a column of soil. In their most basic form these assume one dimensional conduction heat transfer, the soil extending as an infinite domain downwards and assume a known, annual, sinusoidal surface temperature cycle, as shown in for example Carslaw and Jaeger [16]. Often, detailed information on the soil surface temperatures cycle is not available, and only local air temperature data may be used to estimate soil surface temperatures. In the literature, methods have been presented to correlate the soil surface temperature to the measured air temperature or other more easily measured parameters [17,18]. In Jin and Mullens [19] a recent experimental study of the relation between soil surface temperature and air temperatures is provided. The results show that the diurnal air temperature and soil temperature peaks in the upper soil layer lag the soil surface temperature by 2 hours. The findings also show that the diurnal temperature variations are barely noticeable at 25 cm depth into the soil. The notion is made that the relationships between soil moisture, soil temperature, soil surface temperature, and air temperature are not well understood. The results show that there is a low correlation between upper level soil moisture and soil surface temperature and that the correlation between air temperature and upper soil layer temperature is higher than that between air temperature and soil surface temperature.

In Cleall and Munoz-Criollo [20], an analytical solution is provided using the full soil surface energy balance. The derived equations include the effects of soil moisture at the surface. Simplified mathematical expressions are provided for evaporative and convective heat transfer coefficients at the surface, the diurnal and annual solar radiation, and air temperature variation. Their conclusion is that using the full heat balance with a 1D analytical heat conduction model provides a reasonable estimate of soil thermal behaviour.

In Jang and Choi [21], the surface boundary condition is simplified using a convective heat transfer coefficient to the air temperature. The surface heat transfer coefficient is set to 9 W/m^2·K. The authors claim excellent agreement between numerical results and experiments for soil temperature profiles using this boundary condition (depth restricted to 60 cm).

In our study, we investigated the effect of different approaches to the soil surface boundary conditions on the prediction of the thermal regime in the ground. We subsequently looked at the effect of the boundary conditions on the heat transfer between the pipeline fluid and the surrounding soil. In the study, we used measurement data from the soil around a pipeline for verification purposes. The sensitivity of the soil thermal profile to the soil-to-atmosphere boundary conditions was first investigated with a 1D heat conduction model of the soil. This was compared to the measured soil temperature at different depths. The full surface energy balance was estimated from correlations using measured weather data and net radiation measurements. The effect of the choice of soil surface boundary condition representation on the heat transfer between pipe and soil was thereafter determined using a 2D heat transfer model of the soil and pipe. It was a specific objective of the study to determine the effect of using measured air temperature as soil surface boundary condition on the resulting heat transfer between the gas inside the pipeline and the ambient.

2. Methodology

2.1. Background theory and mathematical expressions used

In elementary soil heat transfer, the ground is considered a homogeneous medium into which heat flows vertically through conduction. Fourier law describes heat flow as

$$q_g = -\lambda \frac{dT}{dz} \tag{1}$$

This 1D assumption is only valid if conduction is the sole form of energy transfer and horizontal energy transport does not play a significant role. In reality, the problem is more complex due to the effect of groundwater movement and phase changes occurring during freezing/thawing of soil layers. The presence of the warm pipe (28–30 °C) may affect the assumption of purely vertical heat conduction. The expectation is that at sufficient lateral distance from the pipe the effect is small enough to allow the use of a 1D model.

The temperature regime in the soil upper layer governs the ground thermal regime. This is the zone influenced by the climatic conditions [22]. The basic to understanding this regime is the surface energy balance, defined as

$$q^* = q_h + q_{le} + q_g \tag{2}$$

Here q^* is the net exchange of radiation from the atmosphere to the soil surface, q_h is the transfer of sensible heat from soil surface