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A computational model of thermal monitoring at a leakage in pipelines

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ABSTRACT

Monitoring the surrounding pipeline temperature through fiber optic sensors is an efficient method of detecting leakage of fluid such as oil and gas, from pipelines. This article presents a computational model of temperature monitoring in such a leak detection system (LDS). A longitudinal cross section of an idealized pipe-in-pipe flow-line has been simulated, where a localized thermal source is placed on the lower boundary of the computational domain. The heat transfer rates and temperature profiles of the localized heat source have been investigated because a detailed understanding of the excess temperature surrounding a pipeline is essential in designing efficient leak detection systems based on the active thermometry method. The excess temperature profiles from a localized heat source are studied for various physical conditions. More effective results of the rate of heat transfer have been discussed, which are suggestive for controlling leakages in the pipelines. The present investigation would be useful for leak detection systems.

1. Introduction

Heat transfer analysis in the vicinity of leakages in buried or above ground pipelines is an important research topic for developing leak detection methodology based on optical fiber thermometry. Leakages from pipelines usually produce local thermal anomalies at the vicinity of the pipeline which can be measured using modern fiber optic sensor technologies from a central station located several kilometres away from the site of the leakage. Such a technology involves installing an optical fiber cable parallel to the pipeline over its entire length, which measures the temperature profile in the vicinity of the pipeline. In a state-of-the-art pipe-in-pipe (PIP) system, the flow line is insulated – as depicted schematically in Figure, 1 (insulation). One may idealize such a flow line by an axial cross section (see Fig. 1 (insulation)) so that the complete leakage phenomena may be modeled based on pressure and temperature anomalies in the vicinity of the pipeline. An effective computational model of natural convection heat transfer and fluid flow from a localized source in a porous medium can be used to investigate how the various physical conditions of an insulator may affect the surrounding thermal and pressure anomalies in case a leak occurs. Such a model would also provide useful feedback for optimizing the cost of insulation in a PIP system. For instance, in the Arctic offshore oil companies transport oil/gas at a temperature that is relatively higher than that of the surrounding ocean in the vicinity of the pipeline. Clearly, the natural convection heat transfer is the dominant phenomena that requires further investigation in the context of leakage monitoring in pipelines.

Considering the insulation as a porous medium, a number of numerical (*e.g.* [5,22,23,28]) as well as experimental (*e.g.* [15]) studies are available; most of such studies adopted a uniformly heated bottom wall. Note that studies employing a discrete or localized heat source on the boundary are limited (*e.g.* [5,14,28]). Recently, Oztop et al. [21] reported that both the local inclination angle of the pipeline and the sinusoidal heating at the bottom wall have a significant impact on heat transfer. EI-Khatib and Prasad [14] mentioned that an increase of the stable wall thermal gradient may keep the upper surface thermal energy independent of the Rayleigh number. Saeid and Pop [27] observed an increase in the heat transfer rate with an increase of the length of the heat source. Cotter and Michael [8] investigated the geometrical constraint on the natural convection heat transfer in recently produced crude oil. However, the leakage size in a pipeline is typically unknown and non-uniform, and detailed characteristics of the aspect ratio effect on LDS are not fully understood [10,12,24,25]. Nevertheless, in our recent summary, Bhuiyan et al. [6], and in this article, we present the primary results of a novel computational model that can efficiently analyze various physical conditions, and estimate necessary parameters in order to optimize a leakage or scour detection technique. Moreover, we discuss various controlling or prevention methodologies for leaks in pipelines based on a physical, as well as mechanical, background.

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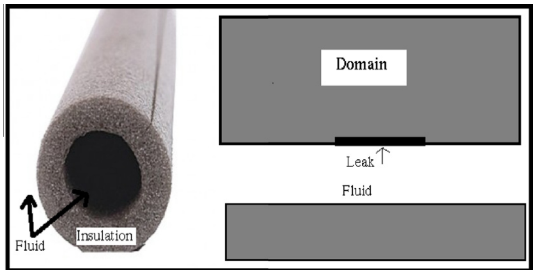

Fig. 1. Schematic diagram at a leakage of a pipe.

2. Formulation of the problem

A fluid saturated porous medium with a localized heat source (see Fig. 1 (domain)) has been considered for the present numerical simulations. The flow is presumed to be laminar, incompressible, and in local thermodynamic equilibrium. The two vertical and upper walls are thermally insulated. The excess temperature vanishes on the lower boundary except over a length of L_hm, where a localized heat source is applied. The present mathematical model is similar to that of Sivasankaran et al. [28] except the momentum and energy equations have been extended; [i.e.]

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\left[\beta\rho g(\theta-\theta_0)\sin\alpha-\frac{\nu}{K}\epsilon u\right], \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\left[\beta\rho g(\theta-\theta_0)\cos\alpha-\frac{\nu}{K}\epsilon v\right], \tag{3}$$

$$\frac{\partial \theta}{\partial t}+u\frac{\partial \theta}{\partial x}+v\frac{\partial \theta}{\partial y}+\left[\frac{\partial \bar{\theta}}{\partial y}v\right]=\kappa\left(\frac{\partial^2 \theta}{\partial x^2}+\frac{\partial^2 \theta}{\partial y^2}\right). \tag{4}$$

Here, u and v are the velocity (m/s) components in the horizontal and vertical directions, respectively, (x, y) are reference coordinates, p is the pressure (pa), ν is the kinematic viscosity $(\mathrm{m}^2/\mathrm{s}), \theta$ is the excess temperature (K), θ_0 is the temperature (K) at a reference state, α is the angle in degrees (°) between the horizontal domain and the horizontal axis, K is the permeability (m^2) of the medium, g is the acceleration $(\mathrm{m}^2/\mathrm{s})$ due to gravity, κ is the thermal diffusivity $(\mathrm{m}^2/\mathrm{s}), \beta$ is the thermal expansion coefficient $(1/\mathrm{K}), \frac{\partial \bar{\theta}}{\partial y}$ is a prescribed vertical rate of variation of θ, t is time (s), L is the horizontal length (m) of the domain, H is the vertical length (m) of the domain, L/H is the aspect ratio, ϵ is the porosity and ρ is the fluid density $\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)$. The boundary conditions are, $\frac{\partial u}{\partial x}=0, \frac{\partial v}{\partial x}=0, \frac{\partial \theta}{\partial x}=0$ at $x=\pm L/2$, and $\frac{\partial v}{\partial y}=0, \frac{\partial u}{\partial y}=0, \frac{\partial \theta}{\partial y}=0$ at $y=H$, and $u=0, v=0, \theta=\theta_0+\Delta\theta$, if $x\in[-L_h/2, L_h/2]$; $\theta=\theta_0$, elswhere. The dimensionless parameters are the Prandtl number, $Pr=\frac{\nu}{\kappa}$, the Rayleigh number, $Ra=\frac{\beta L^3 g\Delta\theta}{\nu\kappa}$, the Darcy number, $Da=\frac{K}{L^2}$, and the Nusselt number (heat transfer at a bottom boundary (surface)), $Nu=-\frac{1}{L}\int_{-L/2}^{L/2}\frac{\partial\theta}{\partial y}(x, y=0)\,dx$.

3. Numerical method and validation

To solve the governing Eqs. (1)–(4), the spatial discretization is done with a weighted residual collocation method that is based on the Deslauriers–Dubuc interpolating scaling functions of degree 6 [7,9,11]. For all reported simulations, we have used a uniformly refined mesh. The time integration is second order accurate and fully implicit. The scheme is free from artificial dissipation, which means that a larger Δt can be used without damping the solution artificially. Instead of solving for each variable (*e.g.* u, v, θ) sequentially at each time step, a Newton–Krylov method is used to solve the nonlinear system that models the multiphysics dependence between the heat, mass, and momentum transfer phenomena [16–20,26,29]. In other words, the numerical method is designed to resolve the multiphysical character of the heat transfer problem. Theoretical details of this method are given by [1–3]; a complete verification of this method for several aspects of heat transfer applications can be found from Alam et al. [4]. This numerical model is often referred to as AWCM++, which has also been verified for several other applications. Since the present article does not contribute toward the development of this numerical scheme, we focus primarily on the simulation results without the details of the numerical method.

To assess the numerical model development in the present study, we have carried out comparisons with previous benchmark dimensionless simulations that have the same physical point of view but a different application. We have accomplished the simulation of fluid flows in an insulator in different cases and positions of the domain, and our code has been collated with earlier verified results for both the localized heat source [13] and the whole bottom boundary heat source [15,23,28].

For high energy transportation computation with a stable linear thermal gradient, our numerical values have been justified with previous standard numerical simulation for the same boundary conditions: localized heat source at bottom boundary while the other boundaries are open, that are shown in Table 1. The values of the heat transfer rates, which have been obtained with respect to the moderate buoyancy driven flow, are shown in Table 2 and Fig. 2. Although the convective heat transfer for Ra = 500 is calculated for this study to be approximately 11% greater than that investigated by Prasad and Kulacki [23], there is good agreement with the results that have been calculated by Bagchi and Kulacki [5] who mentioned that this disagreement is on order of the inertial effects for high energy transportation. Hence, the insulator that we have considered for simulation is relevant for this localized heat transfer and temperature monitoring study.

For the whole bottom boundary heating conditions, our outcomes are in good agreement with the previous investigations shown in Table 3. Since we have studied numerical simulations, we show that our numerical data is in good agreement with the data that has a well match with the laboratory values of Elder [15] in Table 4. However, inverse mesh spacing is considered as a 25.7 that of comparing with earlier study of 25 due to computational convenience. Moreover, numerical results can not be completely removed owing to round off and other errors. Even though there is a slight difference between the numerical data, the physical points of view are the same in the two studies; there is a balance between the buoyancy forces and the viscous forces. Moreover, while the local heat source is producing heat at the leaks in the insulator, it is enraptured in the immediate vicinity of the heated surface by the vertical advection, which is influential in the outer portion of the boundary layer at the localized heated surface.

4. Results and discussion

In the present numerical simulations, the improved localized heat transfer model at a leakage of a monitoring pipe has been established using improved numerical code. For nondimensional comparision, we use the parameter Ra that represents the ratio