Simulation of thermal fields from an underground pipeline at the ground surface

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Abstract. A problem of constructing thermal fields from an underground pipeline located in an inhomogeneous soil and taking into account solar radiation on the day surface is considered. In the model we also take into account the lie of the ground (for example, a trench crossing the underground pipeline) and the effect of the angle of solar illumination. Simulation of such thermal fields is supposed to be used in determining the mechanical damage of an underground pipeline based on the analysis of thermal fields on the day surface.

INTRODUCTION

At present methods of non-destructive monitoring of pipelines based on measuring of the energy eliminated by surfaces are coming to be more important. For that diagnostic a pictures of thermal fields of the earth surface near the pipelines are obtained by heat-sensitive monitors or thermovisual units, which determine the temperatures with accuracy up to part per hundred. These pictures allow to separate out regions with non-uniforms temperature fields.

One of the basic purposes of such monitoring is diagnostic of probably damaged sections of the pipeline. As a rule, the wholeness of the pipe is important and, in general, wear and tear of the pipeline shell is observed. Also, the important problem is detection of leakage. The advantages of heat-sensitive monitoring are safety and low cost. Comparing with an ideal model of heat propagation allows to determine all disturbances of thermal field which are important for operating conditions. Thus, for such comparing it is necessary to get an “ideal thermal field”. In [1] an approach to thermal fields testing is presented. As a result of numerical experiments it was shown [2] that solar radiation is an essential factor to form the thermal field on earth surface.

To study such problems it is very difficult to use analytical methods of obtaining a solution. For example, exact solutions like [3] can not satisfy nonlinear boundary conditions. It is also difficult to satisfy given boundary conditions with special classes of solutions based on known exact solutions [4, 5]. In the works [6, 7, 8] an analytical method is developed for representing solutions in the form of series with recurrently computed coefficients in the powers of special functions. This method was called the method of special series after the works [9, 10]. Using the method of special series, one can solve some initial-boundary value problems [11]. However, the boundary conditions are often have a special form or determined approximately.

One of methods of investigation of thermal fields in different media is direct numerical simulation of thermal diffusivity processes. For further progress in heat-sensitive diagnostic an appropriate mathematical model is required, which takes into consideration most of medium factors forming the thermal field on the ground. The presented paper is devoted to creation of a tool to solve a direct problem of thermal diffusivity in media near the ground with non-uniform heat sources in the media.

Thus, solving and simulating of direct nonlinear problem of heat propagation is an actual problem. In this paper a numerical investigation approach is presented on the base of computational algorithms [12].

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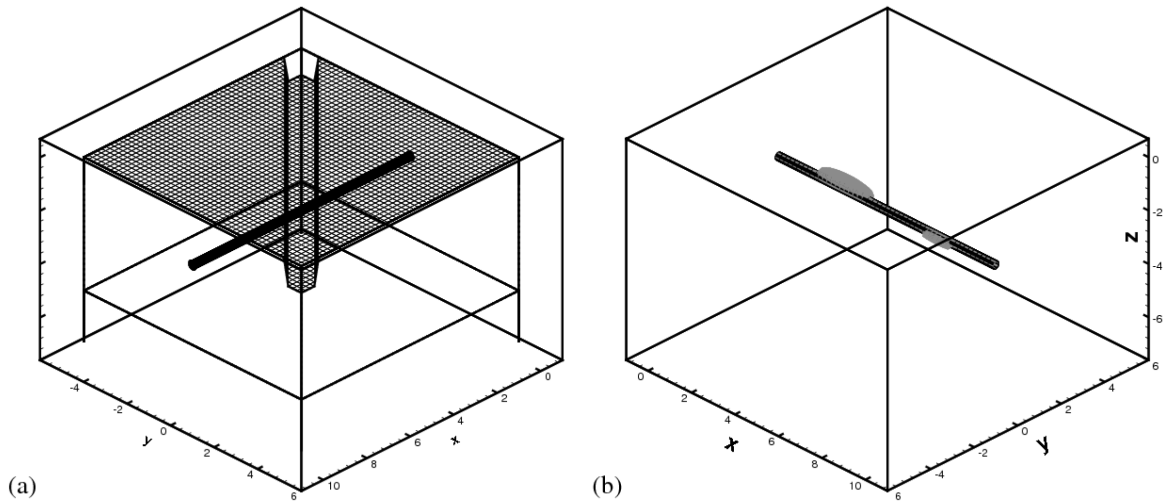


FIGURE 1. A box area with a pipe and a trench (a). Two damaged zones on the shell of the pipe (b).

MATHEMATICAL MODEL

Consider a problem of thermal diffusivity in a media where the heat source is a pipeline with a constant temperature. Suppose that heat flow from the earth (upper) surface is caused by solar energy and difference of temperatures between earth and air. Let consider a parallelepiped (fig. 1).

This problem is described by a linear thermal diffusivity equation:

$$\frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right), \tag{1}$$

where $T = T(t, x, y, z)$ — heat distribution, $\lambda = \dfrac{\kappa}{\rho c_v}$ — thermal conductivity coefficient, κ — heat conductivity, ρ — density, c_v — specific heat.

Suppose that heat flow from the pipeline is proportional to difference of ground and pipeline temperatures, and the coefficient is essentially increased at places where the isolating shell has wear or damaged. Boundary condition at the pipeline has the form:

$$\lambda\frac{\partial T}{\partial \mathbf{n}} = \varepsilon(x)\left(T\Big|_{\text{pipe}} - T\Big|_{\text{media}}\right)\mathbf{n}, \tag{2}$$

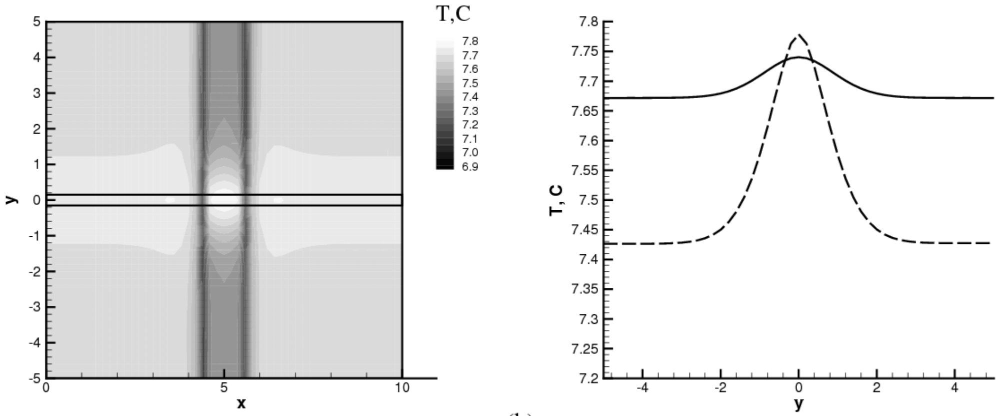
where $\mathbf{n}$ is normal vector to the surface.

Let the pipeline is inside of a parallelepiped (fig. 1). The considered domain may have several layers with different thermal conductivity coefficients. Assume that at the lateral area heat flow equals to zero and at the bottom temperature is fixed. Consider flows balance condition at the upper surface:

$$\alpha q + b\left(T_{\text{air}} - T\Big|_{z=0}\right) = \sigma T^4 - \kappa\frac{\partial T}{\partial z}\Big|_{z=0}. \tag{3}$$

αq is a solar energy which taking up by the ground, b is the coefficient of heat exchange between the surface and air, σ is the Boltzmann constant. The term σT^4 included to the model corresponds to emission of a heated body. Condition (3) makes the considered problem be nonlinear.

A method of numerical simulation of heat diffusivity from the deepen pipeline with a number of damages of the isolated shell is designed. At the damages area the heat flow increases and this area is a heat source and induces thermal nonhomogeneity on the upper surface. To compute heat distribution in a three-dimensional domain the finite-difference method with splitting by spatial dimensions is used [12]. Computations are carried out on orthogonal grid, uniform or adapted by layers. The pipeline position is exactly defined and additional grid points are inserted.



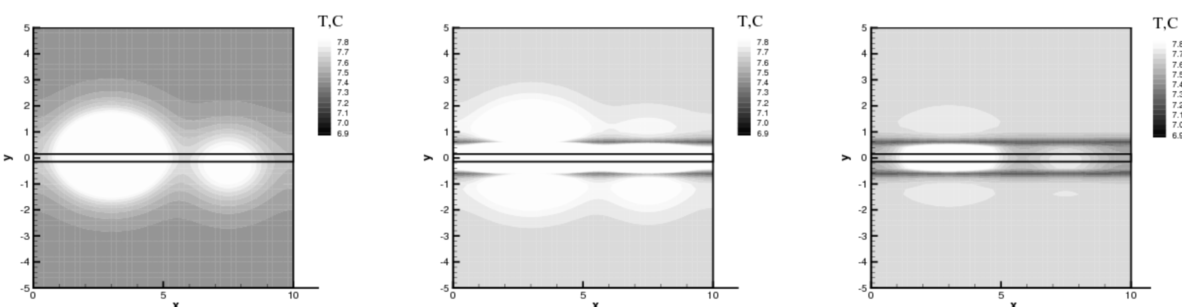
(a) (b)

FIGURE 2. An area with a trench (vertical zone) over a pipe (two horizontal lines). (a) — thermal field on the ground; (b) — profiles of temperature across the pipe: solid and dashed lines are on the ground surface and the bottom of the trench, respectively.

Basic equation is approximated by an implicit finite-difference pattern in each of spatial dimensions. System of linear difference equations has a three-diagonal form and may be solved by a sweep method. Nonlinear boundary condition on the upper surface is included into the system of difference equations. To solve it Newton method is used. The elaborated program allows to carry out computations for different kinds of problems and different materials.

COMPUTATIONAL RESULTS

Let consider a box as a computational area (fig 1) with sizes of 10m·10m·5m wit a pipe. For the soil we will use the following parameters: thermal conductivity is 2,7 W/(m K), specific heat is 2700 kJ/(kg K), density is 2000 kg/m^3. The background temperature of soil is 4–7°C. Air temperature is +7°C. The pipe diameter is 0,3 m, temperature in the pipe is 70°C. There is an insulation shell. We will get the temperature in the box by steady-state computations and consider the thermal trace from the pipeline on the ground surface.



(a) (b) (c)

FIGURE 3. Thermal fields over a pipe with two damaged areas. (a) — no trench, the pipe is at the 2 m deep; (b) — trench is along the pipe, the pipe at the 2 m deep; (c) — trench is along the pipe, the pipe at the 3 m deep.

Figure 2 shows the thermal field on the ground surface with a trench across the pipe. The trench is in the center and perpendicular to the pipe. The trench width is 1 m, the deep is 0,15 m. The trench walls makes two dark(cold) vertical lines with a light (warm) spot on the bottom over the pipe. In fig. 2b the temperature profiles along the y-axis are presented. The solid line is the temperature on the soil surface, the dashed line is the profile of temperature at the trench bottom across the pipe. The peak of the profiles corresponds to the thermal trace of the pipeline on the ground. The amplitude of the thermal trace is greater on the bottom, but the thermal spot (fig. 2a) from the pipe is brighter and may be measured as a local anomaly. It is related, in particular, with the less deep of the pipe shell under the trench bottom. But the thickness of the base of the solid and dashed peaks is the same and it may be a sign of this part of pipeline wholeness.

In fig. 3a the thermal trace on the plane ground surface from a pipeline at the deep of 2 m with two damages of the shell is presented. The scheme of the damages is shown in Figure 1b. The left damage is more intense, the circle of the thermal spot is bigger. In figures 3b and 3c there is the same pipeline structure, but in the figure 3c the deep of the pipe is 3 m The trench is along the pipeline and the thermal trace and the spots are deformed.

Figures 4 shows the same pipe with damages, but the trench is diagonal. The pipe deep is 2 and 3 m in fig. 4a and 4b, respectively. Moreover the solar energy is more intense, whereupon the soil temperature is higher. The thermal picture is not so contrast in compare with the pictures in Figure 3.

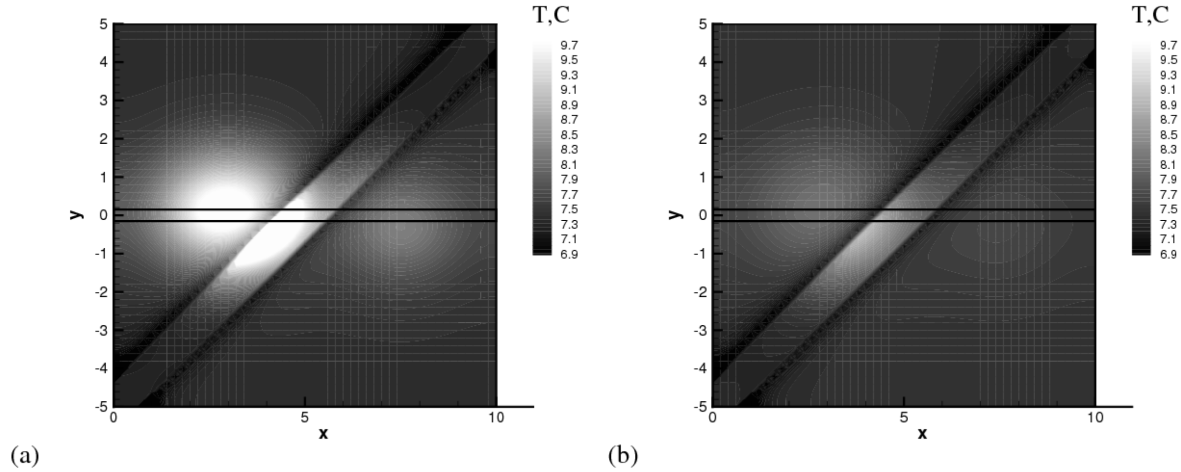


FIGURE 4. Thermal fields on the ground surface with a diagonal trench. The damaged pipeline is horizontal (two parallel lines). The pipe deep is 2 m (a) and 3 m (b).

CONCLUSION

Thermal non-destructive control of a pipeline shell conditions is an important tool for safety, reliability, and environmental protection. Analysis of thermal fields over pipelines has a number of features. A numerical method and a computational code for thermal fields constructing from a deepen pipeline in a soil is suggested, which may be useful for estimations of the thermal insulation wholeness. The case of non-plane surface with a trench is considered. The proposed approaches may be useful for thermal fields analysis and for optimization of thermal control procedures.

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