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A Possibility to Identify Piping Erosion in Earth Hydraulic Works Using Thermal Monitoring

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Abstract

We present the study of the backward piping identification by means of temperature analysis. Thermal monitoring of the earth hydraulic structures is nowadays a very effective and promising method for leakages and erosion process detection. However, piping thermal influence on dams thermal field wasn't investigated deeply. In the paper the results of the extensive numerical computations for the coupled heat and water transport in porous domain with the downstream side pipe opening are described. Computation covered the range of hydraulic diffusivity from 10^{-7} to 10^{-4} m^2s^{-1} and made use of the finite volume method with the Fluent numerical modelization platform. The basis principles of the pipe thermal influences are presented with the evaluation of the possibilities of identifying piping parameters with temperature measurements.

Introduction

Internal erosion as suffusion and piping is one of the main risks for earth dams safety. Of the two modes, piping process is the most dynamic one. We know that a fully pipe opening in the piping process is a very danger state for the dams. It can be finished by the dam rupture. Before this critical state, the pipe develops its length and radius, by the backward erosion process [3]-[5],[8].

Our research was focused on a thermal monitoring possibility of the pipe identification, as well as its dimensions (radius and length) estimation, before pipe fully cross the dams body.

Internal erosion and water flow in the dams are the coupled processes. Erosion process detection and analysis of its dynamic are performed usually by investigation of the dam's hydraulic fields.

Thermal methods for leakage identification and seepage monitoring have proved to be very useful in dams surveillance. They based on the relationship between water and heat transfer. For the null water velocity there is only conductional, slow temperature transport. With rising of the water velocity, temperature from the reservoir is moved quicker with the masse of water (advection process) inward the dam. Variation of temperature distribution in the dam body allows to identify a leakage and even sometimes to estimate a seepage velocity [1], [6], [7].

Thermal monitoring can be realized particularly using the optical fiber as a thermal sensor [1], [2]. For decade the optical fiber installed in dams body have been used as the very effective temperature measurement tool in earth hydraulic works, which allows for spatial continuous measurements.

Piping thermal influence on dams thermal field wasn't investigated deeply [7]. In the paper we present the results of the extensive numerical computations for the coupled heat and water transport in the porous domain, with the downstream side pipe opening. Simultaneously, evaluation of the possibilities of piping dimensions estimation by temperature measurements analysis is described.

Method

Numerical representation of the analysed problem

We modelized an earth hydraulic work with the partial piping which has a downstream outlet and no contact with the upstream water reservoir boundary, as the cylindrical case with the cylindrical hole (Figure 1). Two length of the case, 1m and 10m were modelized. The upstream and downstream charges of temperature and pressure were posed respectively at the inlet and outlet cylinder boundary. Null gravity was used. Various configurations of radius r_p and lengths l_p of the pipe were chosen for different height R and length of the system L. Maximal thermal gradient used in the modelization, between the upstream (inlet) and downstream (outlet) boundaries of the system, equals 20°C and minimal one was 1°C. Two-dimensional axisymmetrical computations allowed to modelize three dimensional cylinder where porous zone was assumed to be isotropic.

In the numerical modelization of the thermal response of the pipe we used the system of the equations which consists of the momentum equation (Darcy equation in the porous domain and Navier Stokes equation in the pipe), the mass conservation equation and the energy conservation equation. The latter, beside the term for conductivity heat transport, obligatory contains also the term describing advectional heat transport (transport of the heat with the mass of flowing water).

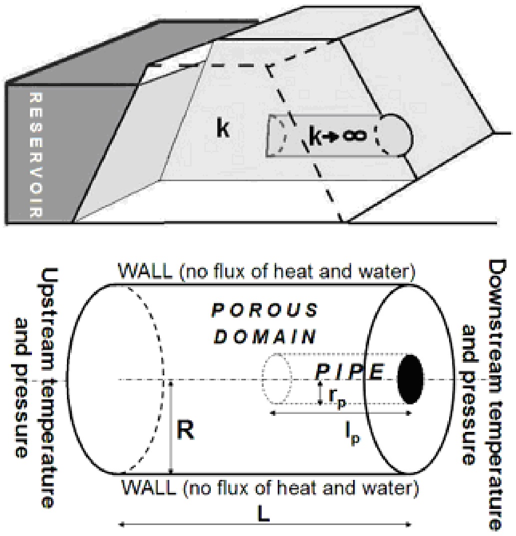


Figure 1: The scheme of the considering system and the simplified cylindrical 3D model used for coupled heat and water transport modelization

The computations were carried out by finite volume method using the FLUENT 6 numerical platform. Four RANS (Reynolds-averaged Navier-Stokes) turbulent flow models (Standard, Realizable, RNG high and RNG low turbulent) and also laminar Navier-Stokes model were investigated to choose the best one for the pipe water flow modelization. Finally turbulent models and laminar Navier-Stokes model comparison showed non significant differences of water flow velocity and in temperature values distribution between these models. Linear model as the fastest one was chosen to the definitive modelizations.

Hydraulic and thermal properties of the porous zone

We defined the hydraulic properties of the modelized cylindrical cage using hydraulic diffusivity D_h calculated in relation to Peclet number. They were calculated for the system without the the pipe. The following reasoning was taken into consideration. If there is a porous zone with known hydraulic properties, what changes in temperature field will show the pipe appearance and its geometrical development? Hydraulic diffusivity to follow the Bousinesq hypothesis is defined as the linear relationship which was calculated for the system without the pipe:

$$D_h = vL = k(H_1 - H_2) \tag{1}$$

where v is the Darcy velocity, L is the length of the seepage path (cylinder's length), k is the permeability and H_1 and H_2 are the upstream and downstream water levels.

The Peclet number describes the relationship between conductional and advectional heat transport. For Peclet number equals 0, there is no flow of water, so no heat water flow transport. Only conductional heat transport is presented. With increasing of water velocity there is more heat which is transported with water, so the Pe values also increases. Peclet number is defined as:

$$Pe = \frac{vC_f L}{\lambda} = \frac{k(H_1 - H_2)C_f}{\lambda} \tag{2}$$

where C_f is the volumetric heat capacity of water and λ is the thermal conductivity of fluid-soil system. This relation is classical for water velocities estimation with the temperatures measurements [6].

As we can see, according to Equations (1) and (2), Peclet number and hydraulic diffusivity are independent from the length of the cylinder.

Three values of hydraulic diffusivity D_h, were modelized for the stationary modelizations from 10^{-7} to 10^{-5} m^2s^{-1} what corresponds to Peclet number range from Pe << 1 to Pe≈ 10.

In the unsteady modelisations we used the hydraulic diffusivity D_h values from 10^{-6} to 10^{-4} m^2s^{-1}. It gives the Peclet number values from Pe ≈ 1 to Pe ≈ 100.

To calculate hydraulic permeabilities for the aforementioned hydraulic diffusivities in the system without the pipe, constant values of upstream and downstream water levels were adopted to modelizations. Same values of the hydraulic conductivity were then used to modelize the system with the pipe.

Results

General view

An analysis of the numerical modelisations results allowed to identify characteristic zones of the pipe thermal influence. Pipe works like a drain. It collects water from the porous domain which conducts water and heat flow. Finally it disturbs the water flow and heat distribution in the porous domain. The example of the water velocity field disturbance due to the pipe presence carried out for hydraulic diffusivity equals 10^{-5} m^2s^{-1} we can see at the Figure 3

In the upstream part of the system, more intensive transport of heat from the upstream boundary towards the upstream end of the hole can be found as the result of the local velocity rising owing to the shortest seepage path.

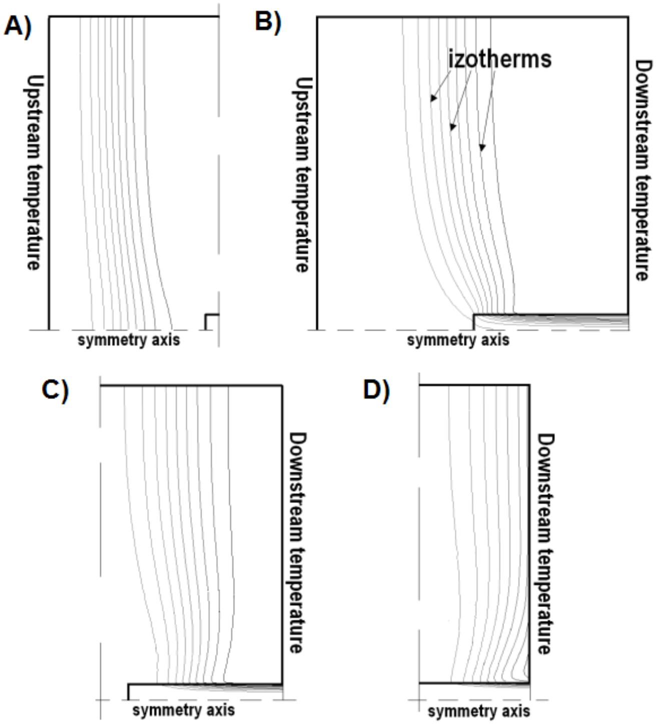


Figure 2: Example of the passage of the thermal front in the high diffusive porous domain obtained for hydraulic diffusivity equals 10^{-4} m^2s^{-1}.

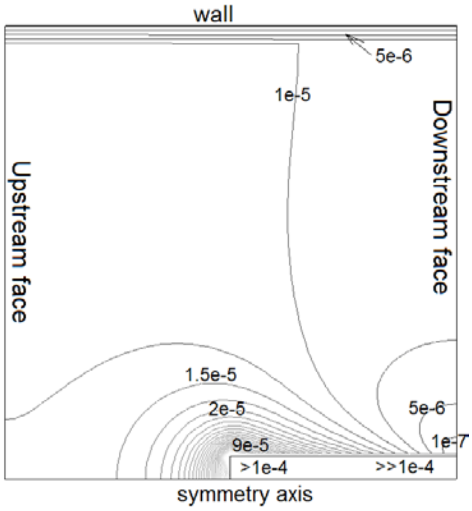


Figure 3: Example of the scalar water velocity field (ms^{-1}) in the porous zone, provoked by pipe presence.

Aside the pipe, depending on seepage velocity vectors values and their directions, we can observe an increasing or oppositely a decreasing of the inlet temperature influence due to the changes in the advectional heat transport direction and its intensity. Finally, because of the heat transport towards the pipe, we observe a heat transport accumulation in the pipe results in the thermal, diffusional pipe influence towards porous domain.

Zone between upstream end of the pipe and reservoir boundary

As it was mentioned above, due to the shortest seepage path in the considered system, from the upstream system's limit to the upstream end of the hole, the zone of stronger upstream temperatures influence is created. This zone is visible at the Figure 2A and 2B close to the upstream end of the pipe. On this figure the system length equals 10m. The pipe radius and length of the pipe equals respectively 1cm and 50cm. The relevant zone has a form of the funnel with the tip connected with the end of pipe. The important temperature changes in this zone can be detected for hydraulic diffusivity 10^{-4} m^2s^{-1}, at the extension of the pipe axe, close to the upstream end of the pipe. For the pipe length equals from 10% to 30% of the system length the significant temperature changes are localized in the limited zone close to the upstream end of the pipe, starting from the upstream end of the pipe towards the water reservoir. However, for the pipe length equals about 50% of the system length and longer one, important changes in thermal field touch almost up-stream boundary of the system.

Zone aside the pipe

This is the zone where we observe the pipe hydraulic influence on the seepage velocity vectors which are directed obliquely towards the pipe.

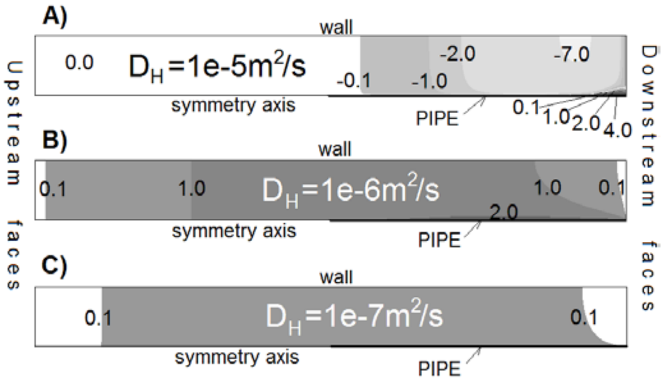


Figure 4: Values of the thermal influence of the pipe for different hydraulic diffusivity values carried out in steady state modelizations.

Depending on the value of the hydraulic diffusivity of the soil it results in two basic opposing thermal effects aside the pipe. The first one, an increasing of the inlet temperature influence, is characteristic for the hydraulic diffusivity (defined for the cylinder without the pipe) of order of 10^{-6} m^2s^{-1} and lower. It corresponds to a conductional heat transport without advection domination.

For this range of hydraulic value, an appearance of the pipe and its development accelerate not very much seepage velocity in porous domain. In effect, heat from the upstream part of the system aside the pipe is transported quicker to the downstream part of the porous zone, not directly towards the pipe boundary. Moreover a heat accumulation in the pipe results in the diffusional external pipe thermal influence which amplifies an increasing of the inlet temperature influence close to the pipe. Thermal intensity of this zone and its dimensions depends strongly on the temperature gradient between upstream and downstream, the length of the pipe and the length of the system. This thermal effect is presented at the Figure 4B and Figure 4C. Positive and negative values mean respectively increasing or decreasing of the upstream face temperatures influence in degrees of the Celsius. Inlet and outlet temperatures equal 25°C and 5°C respectively.

Described above, thermal influence of the pipe starts to be relatively significant and large in space for hydraulic diffusivity of order of 10^{-6} m^2s^{-1} and for system minimum length of order of 10m, and for pipe length equals minimum 50% of the system length. For longer length of the system a significant temperature changes are visible even for hydraulic diffusivity equals 10^{-7} m^2s^{-1} and lower.

The second type of the thermal zone aside the pipe is characterized primarily by inlet temperature influence decreasing. It is developed for hydraulic diffusivity (defined for the cylinder without the pipe) of order of 10^{-5} m^2s^{-1} and higher. It corresponds to advectional heat transport domination. For this range of hydraulic value, mass of water from the porous zone aside the pipe is transported quicker and more directed towards the pipe. It results in very fast seepage velocity reduction in the porous zone, along the pipe, towards the downstream system boundary. Because of the same direction of simultaneous advectional coupled heat transport decreasing, the zone of the upstream temperature (reservoir boundary temperature) influence deficiency is created. This zone is visible at the Figure 4A and at the Figure 2D aside of the downstream outlet of the pipe. In other words, we observe there an increasing of the downstream temperature (air temperature) influence. It is very important to correctly interpret this fact during the passive temperature measurements analysis. Important and deep influence of the downstream temperature in the corps of the earth hydraulic work always signifies low leakage or no leakage zone. However, we see that it can be also the sign of the close presence of the backward piping process.

Thermal intensity of described zone and its vertical and horizontal dimensions depend particularly on the temperature gradient between upstream and downstream, the length of the pipe and the length of the system. Influence of the pipe radius is less important but must be taken also into consideration. We can see these relations at the Figure 5, where numerical simulation were carried out for inlet and outlet temperatures equal 25C and 5C and for diffusivity equals 10^{-5} m^2s^{-1}. Figure 5A and Figure 5B presents the results obtained for the length of the system equals 1m and 10m, respectively.

An observed inlet temperature influence values increasing with the length of the system increasing can be used probably to pipe thermal identification in the large hydraulic works. However, significant influence can be detected for the minimum system length about 10m, and for the pipe length equals minimum 50% of the system length.

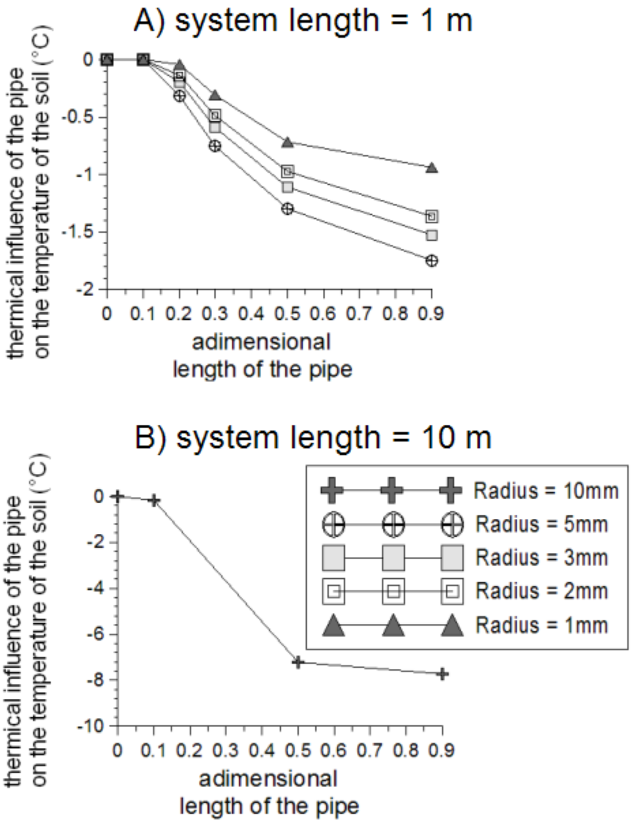
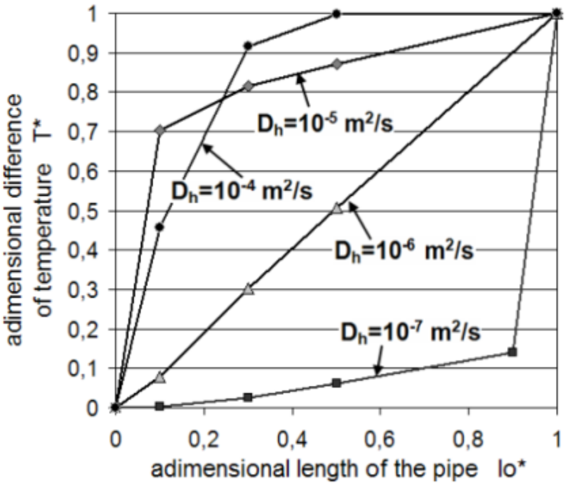


Figure 5: Maximal values of the inlet temperature deficiency in the field of the thermal influence of the pipe versus adimensional length of the pipe obtained in steady state modelizations.

Thermal zone at the outlet of the pipe

As it was mentioned, pipe drains the heat with the mass of water from the porous zone. It results in the accumulation of heat in the hole which is transported outside of the pipe with velocities much higher than in the porous domain. There is significant difference between temperatures inside and outside the pipe which rises in the direction of downstream outlet of the hole, to reach its maximal value close to the outlet. Variation of the temperature in this point is very characteristic and it can be measured easily in the pipe outlet flow.

We found that besides hydraulic diffusivity value of the porous domain and temperature gradient between upstream and downstream, this is the adimensional length of the pipe which is essential for the pipe outflow temperature. We can see it at the Figure 6 and 7 where adimensional length of the pipe is defined as the relation between the length of the pipe and the length of the system. Numerical computations were realized for the system length and height equals respectively 1m and is 1m and for the pipe radius equals 5cm. Simultaneously, very low influence of the radius of the pipe has been identified (Figure 8). This important relationship between outlet temperature and adimensional length of the pipe is visible in a full range of tested hydraulic diffusivity from 10^{-4} to 10^{-7} m^2s^{-1} (hydraulic diffusivity value calculated for the system before pipe occurrence) and even for a small temperature gradient between upstream and downstream faces.

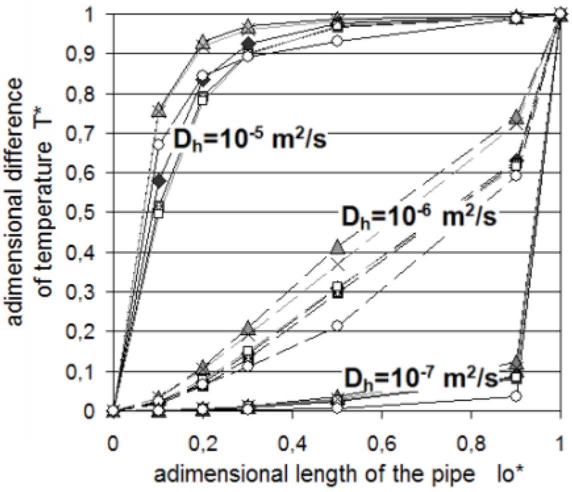


$$lo^* = \frac{l_0}{L} \qquad T^* = \frac{Max(T_{out} - T_{out\ with\ hole})}{Max(T_{out} - T_{in\ with\ hole})}$$

Where: l_0 – length of the pipe
L – length of the system
T_{out} – temperature at the pipe outlet location, however without pipe temperature influence
$T_{out\ with\ hole}$ – temperature of the pipe outlet flow
$T_{in\ with\ hole}$ – temperature at inlet of the pipe in the case of full pipe opening, which equals to inlet boundary temperature

Figure 6 : Adimensional differences of the pipe outlet flow temperature versus adimensional length of the pipe obtained for unsteady state modelizations and for the minimal and maximal step temperature equals respectively 25°C and 5°C.

In contrast to the aside pipe thermal influence, the variation of temperature in the pipe outlet flow is dominated always by heat from the upstream system boundary. In steady and unsteady modelizations, maximal temperature differences measured in the pipe outflow, increase significantly for the pipe length development. However, kinetic of this process depends strongly on the value of the hydraulic diffusivity (defined for the system before the pipe appearance).

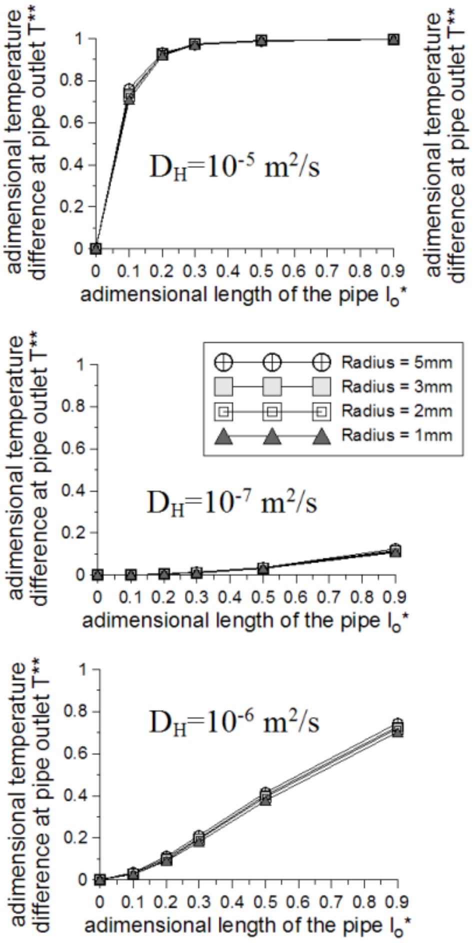


Line	Inlet temperature [°C]	Outlet temperature [°C]	Length of the system [m]	Height of the system [m]
—△—	25	5	1	1
—◆—	10	5	1	1
—⊠—	6	5	1	1
—□—	5	25	1	1
—×—	25	5	1	0,25
—○—	25	5	10	1

$$lo^* = \frac{l_0}{L} \qquad T^* = \frac{T_{out} - T_{out\ with\ hole}}{T_{out} - T_{in\ with\ hole}}$$

Figure 7 : Adimensional differences of the pipe outlet flow temperature versus adimensional length of the pipe for steady state modelizations.

In the case of small hydraulic diffusivity of order of 10^{-7} m^2s^{-1}, pipe length development influences weakly the outlet flow temperatures, practically until full pipe opening. Just before it, inlet temperature domination raises very quickly. For hydraulic diffusivity 10^{-6} m^2s^{-1} this relation rises systematically for all lengths of the pipe. Finally for hydraulic diffusivity 10^{-5} m^2s^{-1} and higher, so for important advectional heat transport domination, even small the pipe length development influences very strongly outlet flow temperatures. When adimensional length of the pipe equals about 0,2, it starts to loose its growth trend. And for adimensional length 0,5 and higher this influence of the pipe length development is small or even null, depending on the hydraulic diffusivity values.



$$L^* = \frac{l_o}{L} \qquad T^{**} = \frac{T}{T_{inlet} - T_{outlet}}$$

Figure 8 : Adimensional temperature differences in the pipe outlet flow versus adimensional length of the pipe for different radius of the pipe obtained in steady state modelizations.

Conclusion

In the paper we presented the base principles of the backward piping influence on the thermal field of the earth hydraulic structure. The research results show a possibility of the backward piping thermal detection and its kinetic and length assessing. The investigations were performed for the whole range of hydraulic diffusivity which can be found in an earth structure as well for numerous combinations of pipe dimensions versus system dimensions.

The easiest and the most effective thermal method for the pipe length and its kinetic identification is an analysis of temperature of the pipe outlet flow, which strongly depend on the adimensional length of the pipe, and practically not depends on the pipe radius. It is limited of course by the necessity of the first pipe outlet localizing at the downstream face of the earth hydraulic work.

The pipe aside thermal influence in the porous zone can be used to the pipe existing detection. However, precise estimation of the pipe's dimensions can be difficult, taking into account the numerous parameters which influence this zone temperature values. Moreover, it is important to notice that decreasing of the system inlet (upstream boundary) temperature influence in this zone, as well a deep system outlet (downstream boundary) temperature penetration, they can signify not a no leakage presence but contrary, pipe existing and its development close to the thermal sensor.

Presented results should be verified in field observations of the relevant problem.

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