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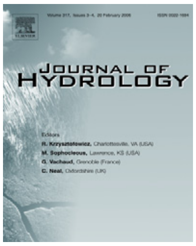

Intra-hole fluid convection: High-resolution temperature time monitoring

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Summary Intra-hole convection was monitored in detail by a string of five high resolution temperature probes arranged in an 8-m long unit lowered step-by-step into a slim experimental borehole. The experiment was performed in the test hole Sporilov (Prague). A 50-m long depth interval (between 80 and 130 m) was covered in five successive steps. The hole itself is 150 m deep and 112 mm in diameter. The experiment occurred in the internal plastic tube 5 cm in diameter which is sealed from the influx of ground water in the surrounding strata. In the studied interval the temperature gradient varies in the range of 0.020–0.0215 K/m. The borehole was drilled in 1993 and has been in equilibrium since then. Temperature as a function of time was sampled in 15 s intervals and the individual measuring steps took from 1.5 to 2.5 days, each temperature time series thus contained 9000 up to 16,000 data points. The obtained results revealed: (1) temperature–time series present a complex apparently random oscillation pattern with the amplitude of up to 0.045 K; (2) the statistical analysis confirmed a quasi-periodic skeleton of a two-frequency oscillation structure. Shorter periods of 10 up to 30 min are superposed on longer variations with period of several hours. (3) The quasi-periodicity may be hidden under a considerable amount of noise. (4) Within the studied interval the quasi-periodic convection may alternate with a relatively ''quiet'' regime when temperature oscillations decreased to only 0.004–0.01 K range. (5) Regardless of certain deterministic rules present in the dynamics, the bulk of temperature variations are chaotic.

Introduction

Temperature data obtained from borehole logging provide an essential input to many fields of engineering, exploration and research. In addition to large-scale environmental signals temperature logs may yield the evidence of fine temperature–time changes associated with heat transfer conditions in a compositionally heterogeneous subsurface strata as well as with a small-scale natural convection in a water filled borehole. Even when measured temperature-depth $T(z)$ profiles offer the basic information on the

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subsurface temperature field and provide useful information for e.g. heat flow calculation, the observed tiny temperature time variations may present new valuable material for fluid dynamics behavior studies.

The need of a thorough interpretation of the fine scale structure of the temperature signal has been recognized a long time ago (Haenel et al., 1988). The first investigations were focused on imposing the limits of the accuracy to what temperature has to be measured when logging holes of different diameters. Today the problem has broadened to a variety of contexts (such as e.g. non-linear heat transport in heterogeneous subsurface) and has several potential implications both in theoretical geophysics and practical industrial applications.

The intra-hole fluid movement responsible for at least a part of the fine scale temperature variations can be discriminated as a generally deterministic process that operates on relatively short time scales with characteristic times varying from few seconds up to several days (see e.g. Bodri and Cermak, 2005, and a number of references therein). In the presence of the geothermal gradient in a borehole relatively heavier cold fluid located above warmer and lighter fluid is forced to move downwards, the release of potential energy provides kinetic energy for the motion and the system becomes unstable. This instability is opposed by the frictional action of the fluid viscosity. The motion occurs only when the destabilizing effect of the temperature difference is strong enough to overcome these obstacles, in other words, when the geothermal gradient exceeds a certain critical value.

In the present work we report on the micro-temperature fluctuations detected in the test borehole Sporilov (50° 02.43′N, 14° 28.65′E, 270 m.a.s.l., Prague, Czech Republic). By applying modern computational techniques to the observed time series we tried to quantify the details of the instability of the intra-hole water column. Except of the detection of the fluid dynamics, this experiment may contribute to the general evaluation of the accuracy limits of temperature logging in general and help to understand how geothermal data are to be applied to infer environmental characteristics, such as e.g. subsurface temperature response to the surface (climate) changes or the details of stratigraphy.

Background

Commonly cited formulation of the critical gradient G_c looks as follows (Diment, 1967; Gretener, 1967):

$$G_c = \frac{g\alpha T}{c_p} + \frac{B\nu k}{g\alpha r^4}, \tag{1}$$

where g is the acceleration, T is the absolute temperature, r is the radius of borehole, and B is the system specific constant. For small radius-to-height ratio boreholes this constant equals to 216. Other parameters characterize physical properties of borehole fluid: α – the coefficient of thermal expansion ($2.13 \times 10^{-4}\,\mathrm{K}^{-1}$ for water), c_p – the specific heat (4182 J/kg K), k – the thermal diffusivity ($0.143 \times 10^{-6}\,\mathrm{m}^2/\mathrm{s}$), ν – the kinematic viscosity ($1.15 \times 10^{-6}\,\mathrm{m}^2/\mathrm{s}$). The first term in (1) is the adiabatic gradient, small enough ($\sim 10^{-2}$ K/km) to be exceeded in most water filled boreholes. The second term takes into account the fluid viscosity and is sensitive to the radius of the hole. It increases from 2.7 to 21.0 K/km with a decrease of the borehole radius from 5 to 3 cm. Because geothermal gradient generally exceeds these values it is clear that the thermal instability is a characteristic phenomenon for most boreholes under normal geothermal conditions.

The mode of the intra-hole convection can be determined by the set of three dimensionless parameters. The Rayleigh number

$$Ra = \frac{g\alpha(T_2 - T_1)d^3}{\nu k}, \tag{2}$$

where d is the characteristic length; $(T_2 - T_1)$ is the temperature difference across the characteristic length. The value d is generally assumed to be the vertical length of convectional cells, their horizontal extent being limited by the diameter of the hole. For a short cell its vertical length may be a few times the diameter of the hole, though for the most situations the ratio of vertical to horizontal cell extent is actually greater (Balmforth and Biello, 1998).

The second parameter is the Prandtl number

$$Pr = \nu/k, \tag{3}$$

that is the property of the particular fluid and not of the flow. As the Prandtl number decreases, relatively more rapid heat diffusion compared with the vorticity can be observed. Most fluids have Prandtl number greater than 1, but it may vary widely. Water, that generally fills boreholes, is typically at the low end of the range of the Prandtl numbers ($Pr = 8$).

Finally, the depth of the borehole h is another relevant parameter even when it is much larger compared with the diameter D. Both quantities appear as so-called aspect ratio $A = h/D$ (for boreholes typically $A \gg 1$). Three parameters Ra, Pr and A govern the convection model, providing dynamical similarity of the intra-hole convection in different systems.

Instability occurs when the Rayleigh number exceeds its critical value, below this value the fluid remains in equilibrium. For low Prandtl numbers the critical Rayleigh number is above $2\text{–}5 \times 10^3$ at least for the aspect ratio between 10 and 100 (Vest and Arpaci, 1969; Tritton, 1977). Exact critical value of Ra for the onset of convection is system dependent and should be assessed for a given case. For example, one of the specific features of the intra-hole convection is that the viscous drag of the walls tends to restrain motions near the wall. It is reflected in the increase of the critical Rayleigh number for the onset of convection and in the simplification of its pattern. Our estimations based on previous experiments performed in the Sporilov hole have revealed above-critical Rayleigh numbers between 2.5×10^4 and 2.5×10^8 for d between 0.1 and 1 m that hints the possibility of certain fluid instability (Cermak et al., 2007a,b).

The intra-hole dynamics is determined by stability properties of convection and, in principle, temperature fluctuations caused by the intra-hole convection can be recorded by a high-resolution temperature monitoring. The intra-hole convection can be presented as a system of more or less long cells, and the fluid motion presents a set of more or less similar orbits rather than single trajectories. The fact