



Determination of local values of heat transfer coefficient in geothermal models with internal functions method



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ABSTRACT

The objective of this study is to determine the depth characteristic of a heat transfer coefficient in the wellbore heat exchanger with the use of the original calculation procedure called an internal functions method. During the geothermal heat recovery, the substances change their pressure and temperature together with current (local) depth of the wellbore. Together with a change of these thermophysical parameters, there are also changes in the substance thermophysical properties, i.e.: specific heat, heat conductivity, density and viscosity. These properties decide on Prandtl Pr and Reynolds Re criterion numbers. These numbers, in connection with Nusselt number, enable to determine the local values of the heat transfer coefficient. The values of thermophysical properties and a heat transfer coefficient, assumed in the calculation models of the geothermal heat recovery, usually have a decisive influence on the reliability of the obtained results.

In the considered case, the value of the heat transfer coefficient has changed – from the depth of 500 to the depth of 2100 m – by about 70%. Therefore assuming the constant value of this coefficient in the simulation models of the geothermal heat recovery is a significant simplification that may considerably affect the calculated effectiveness of the geothermal systems.

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1. Introduction

Geothermal energy in the form of dry steam or high-temperature liquid water has been exploited for decades to produce heat and electricity. Development of geothermal energy is hindered by the high cost of drilling, necessity of waste water utilization, corrosion and scaling in wells and surface installations. The above-mentioned problems can be solved by application of wellbore heat exchangers in abandoned gas and oil wells [1,2]. In this kind of installation, fluid circulates in a closed loop extracting heat from casing of well. The use of the abandoned wells reduces the cost of drilling, while a closed circulating system, in which working fluid has no contact with rocks, prevents geothermal fluid production, scaling and corrosion. A wellbore heat exchanger, presented in Fig. 1, is composed of two concentric pipes. A casing of wellbores is used as the outer pipe of the exchanger. The inner pipe with a relatively smaller diameter forms an inside channel called a recovery well. The annular space between the outer and inner pipe

forms an injection well. The outer wall of the inner pipe is wrapped with insulation and the bottom of the wellbore is closed. The working fluid flows into the injection well and is gradually heated. At the bottom of the wellbore, the fluid is returned to the recovery well and flows into the wellhead [3].

Evaluation of geothermal power production from retrofitted abandoned wells requires building a numerical model. A critical parameter of such model is a heat transfer coefficient, which decides on the amount of heat exchange between the casing of the wellbore and the fluid circulating in the system [4]. Determination of its correct value is a challenging task because it is a function of fluid thermophysical properties which, in turn, are pressure and temperature dependent.

While recovering the heat from the deep geothermal wellbores, the pumped-in fluid changes its temperature (geothermal effect) and pressure (gravitation effect) together with the depth; it may also change its physical state. Local values characterising the fluid thermophysical properties depend on local (variables with the depth z) values of temperature and pressure.

In the analytical description of the heat and mass flow, the following thermophysical properties of the substance are, among

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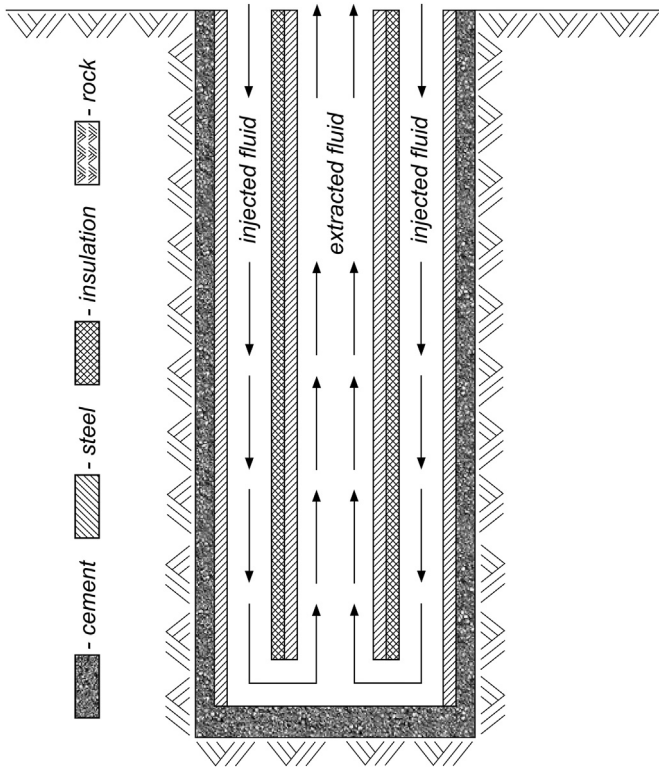


Fig. 1. Schematic diagram of the wellbore heat exchanger.

others, of the major importance: specific heat c_p , thermal conductivity λ , density ρ and kinematic viscosity ν . One of these thermophysical values – density – affects the local mass flow $\dot{m}(z)$:

$$\dot{m}(z) = w \cdot \rho(z) \cdot A \quad (1)$$

where: A – channel cross-section, and w – fluid rate, as well as local pressure $p(z)$:

$$p(z) = p_a + \rho(z) \cdot z \cdot g \quad (2)$$

where: p_a – ambient pressure, g – gravitational acceleration.

The substance thermophysical values decide on the heat transfer intensity which in case of forced movement depends on Nusselt criterion number Nu in the form of:

$$Nu = \frac{h \cdot L}{\lambda} \quad (3)$$

where: h – heat transfer coefficient, and L – characteristic dimension of the heat transfer model. For the fluid forced flow in the pipe, Nusselt criterion formula can be assumed in the form developed by Colburn [5]:

$$Nu = 0.023 Re^{0.8} \cdot Pr^{0.33} \quad (4)$$

which is true for $10^4 < Re$ and for $0.7 < Pr < 160$, where numbers Re and Pr are expressed with the dependence:

$$Pr = \frac{\nu \cdot c_p \cdot \rho}{\lambda} \quad (5)$$

$$Re = \frac{w \cdot D}{\nu} \quad (6)$$

where: w is a fluid rate averaged over the pipe cross-section with the diameter $D(=L)$. While combining Formulas (3) and (4), the dependence on the heat transfer coefficient is obtained:

$$h = 0.023 \lambda \frac{Re^{0.8} \cdot Pr^{0.33}}{D} \quad (7)$$

The substance thermophysical properties are non-linear functions of the thermodynamic parameters: temperature T and pressure p ; frequently – near the substance phase transitions – these functions become strongly non-linear. The changes in some thermophysical properties values only within a one-phase range, may exceed several hundred percent (e.g. c_p of water). In Table 1, for comparative purposes, there are presented the thermophysical values of water in both a liquid and gas phase under isobaric and isothermal equilibrium. The water density presented in Table 1 was determined based on the Wagner and Pruss state equation [6], whereas the kinematic viscosity and heat conductivity coefficients were determined based on dependences of Huber et al. [7,8].

It results from Table 1 that at significant changes in the substance temperature and pressure, the acceptance of the averaged values of the individual thermophysical parameters results in substantial errors in the heat and mass flow balances. Therefore, aiming at finding their local and momentary values is a calculation problem itself.

In the available literature, there is no discussion about the pressure and temperature influence on thermophysical properties of fluid working in the geothermal system and, as a consequence, on the magnitude of the heat transfer coefficient. Part of the geothermal models makes the heat transfer coefficient value independent of pressure and temperature changes [9–11] or, as a simplification, it assumes its constant value [12]. Alimonti and Soldo [13], while analysing the possibility of using the wellbore heat exchanger in geothermal systems, compared the results received for the constant thermophysical properties of the fluid with the results considering their dependence on temperature. Both the temperature and pressure influence on the fluid thermophysical properties was considered by Davis and Michaelides [14] as well as Cheng et al. [15] who simulated the operation of the geothermal systems using isobutene in the abandoned oil wells. However, in both studies there is no comment allowing estimation of the influence of the local pressure and temperature on the received results, including the amount of the heat transfer coefficient.

Typically – in the generally available literature sources, e.g. Refs. [16,17], for substances commonly used in the thermal technology – there are given the tabled values of the thermophysical amounts $c_p(T_i)$, $\lambda(T_i)$, $\rho(T_i)$ and $\nu(T_i)$ in the function of selected discrete values of temperature T_i , at pressure p_a , similar to the atmospheric one. The data, at slight changes of pressure, is the basis for determining the temperature characteristics: $c_p(T)$, $\lambda(T)$, $\rho(T)$ and $\nu(T)$, usually in the form of higher degree polynomials, true in the selected range of initial T_p and final T_k temperature.

In the cases when, apart from the temperature, the substance pressure changes as well, the above-mentioned thermophysical amounts become the functions of two variables: $c_p(T,p)$, $\lambda(T,p)$, $\rho(T,p)$ and $\nu(T,p)$. Then, it is possible to use the tabled discrete values $c_p(T_i,p_j)$, $\lambda(T_i,p_j)$, $\rho(T_i,p_j)$ and $\nu(T_i,p_j)$; the strongly reduced data for a small number of selected substances may be found in the literature. “The size” of such tables depends on the number of discrete arguments T_i and p_j , for which the thermophysical values were determined experimentally or analytically. In the cases when the substance values T_i and p_j do not appear in the table, the values of the local thermophysical amounts may be determined by means of an approximation method in the discrete field $\Delta T = T_i - T_{i-1}$ and

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