On Calculation of a Steam—Water Flow in a Geothermal Well

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Abstract—Approaches to calculation of a steam—water flow in a geothermal well are considered. For hydraulic applications, a WELL-4 model of a steam—water well is developed. Data obtained using this model are compared with experimental data and also with calculations by similar models including the well-known HOLA model. The capacity of the A-2 well in the Mutnovskoe flash-steam field (Kamchatka half-island, Russia) after planned reconstruction is predicted.

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INTRODUCTION

Utilization of deep heat of the earth is a rapidly and successfully developing area of power engineering. In 2010, the energy output of geothermal power plants (GPPs) worldwide was higher than $10^4$ MW and stably increased by 300 MW a year [1]. In Russia, five GPPs are harnessed: three in Kamchatka (76 MW) and two in the Kuril islands (7.2 MW). In all the Russian GPPs, as well as in the majority of GPPs throughout the world, the heat carrier coming from the earth’s interior through production wells is a steam—water mixture. The presence of a two-phase heat carrier requires the solution of a variety of problems concerning steam—water flows. A key point here is calculation of the flow in wells used to measure the parameters of a geothermal tank at the wellhead and prediction of the wellhead parameter variation during field development.

The task that faced the authors in this work was to predict the capacity of the A-2 well in the flash-steam Mutnovskoe field (Kamchatka) for estimation of the reconstruction efficiency. This well, 1564 m deep, was exploited from time to time for 9 years because of the improperly constructed ground-surface pipeline for mixture transportation. Frequent temperature variations degraded the pressure integrity of casing columns, and the well was taken out of service. Note that compensation for heat carrier losses by constructing a new well may cost as much as 200 millions rubles without assurance of successful drilling-in. Therefore, it was suggested that the well be reconstructed by installing a new smaller diameter casing column to a depth of 1200 m so that producing zones are below the section to be reconstructed. In other words, it is assumed that the dependence of the flow rate on the pressure varying with depth remains unchanged. In this case, the post-reconstruction capacity can be predicted in two steps. First, the pressure at a depth of 1200 m is calculated using the well flow rate parameters measured versus the wellhead pressure before reconstruction. Then, using the depth dependences of the flow rate parameters and pressures, the wellhead pressure is calculated after reconstruction. In this way, we obtain a new dependence of the flow rate parameters on the wellhead pressure. Certainly, such calculations imply the availability of an adequate model of the flow in a steam—water well.

From the standpoint of hydraulics, wells are vertical (sometime inclined) circular tunnels (tubes). Most frequently, they resemble a telescope in that their diameter grows from the bottom (lower end) to the head (upper end). Calculating steam—water flows is a challenging problem that cannot be solved without using empirical formulas. However, empirical formulas can provide correct results only if they meet experimental conditions. Experiments in producing steam—water wells are extremely limited both qualitatively and quantitatively. Aiming at qualitative adequacy of computational models causes an increase in the number of empirical formulas, and the lack of relevant experimental data casts doubt on the quantitative adequacy of the models.

Thus, two problems were solved in this works: development of a steam—water flow model meeting the conditions of the Mutnovskoe field and prediction of the capacity of the A-2 well upon reconstruction.

1. SYNOPSIS OF AVAILABLE MODELS

When analyzing a steam—water flow in a well, researchers usually adopt the quasi-stationary conditions. In other words, it is assumed that a given model
is essentially stationary but the parameters of interest may slowly (relative to the characteristic time of hydrodynamic instability) vary with time because of well–rock heat exchange. From observations and theoretical calculations [2], one can estimate the characteristic time of hydrodynamic instability, which equals several tens of seconds. Since we are interested in those time intervals of the well performance far exceeding several tens of minutes, the adopted quasi-stationary conditions seem to be logical.

A steam–water flow may exist both throughout a well and within only its upper part below which the heat carrier is in a liquid state. A true steam–water flow can be considered as the particular case when two (steam–water and water) parts coexist. Therefore, the latter situation in the well can be viewed as the general case. In addition, the purely steam flow is sometimes taken into account. However, the speculative case of alternating steam and steam–water sections is of little practical interest, since calculation under these conditions can be conducted for a purely steam well with a sufficiently high accuracy.

Difficulties in flow calculation in wells are associated with the presence of the steam–water section. Note that the vapor content in a steam–water flow in wells may vary in wide limits. As the heat carrier goes up, it experiences an intense phase transition, since the pressure drops. Therefore, all main patterns of the steam–water flow may be observed in one well [3]. Importantly, the diameter of wells is large. Experiments show that final results depend on the diameter of the tube, while attempts to extend experimental data for tubes of any diameter failed. Moreover, such a conceptual issue as the separation of main flow patterns is based on experimental data obtained in thin-walled tubes and the question of whether there exists, e.g., a classical projectile flow in large-diameter tubes, remains open. Care should be exercised when using empirical formulas to characterize the flow in wells. It is desirable to use no more than two or three such formulas and replace them by relationships based on reasonable assumptions.

Pioneering steam–water flow calculations were aimed at determining the depth of vaporization, which was associated with the water level in a usual flowing well [4]. Without going into details of such an analogy (when stated rigorously, this problem is not so simple as it appears in [4]), we only note that, when the enthalpy of the mixture changes slightly within the steam–water section, one can easily find the pressure at the depth of vaporization from the enthalpy measured at the head according to the saturation line. Knowing this depth and the pressure at it, it is easy to determine the bottom pressure, since to do this it suffices to analyze the flow within the purely water section: from the bottom to the depth of vaporization.

In the general case, the depth of vaporization can be determined from the formula

\[
L = \frac{p_0}{\frac{1 - A}{2 \tau_w} \rho g} \int_{p_w}^{p_m} \frac{dp}{R},
\]

where \( L \) is the depth of vaporization, \( p_m \) and \( p_w \) are, respectively, the wellhead pressure and the pressure at the depth of vaporization, \( R \) is the radius of the tube, \( \tau_w \) is the shear stress at the wall of the tube, \( \rho \) is the density of the mixture, \( g \) is the free-fall acceleration, and \( A \) is a function characterizing acceleration (the fraction of the acceleration component in the total pressure drop).

The integral in formula (1) can be taken analytically in some cases. For example, in [5], where a homogeneous model assuming thermodynamic phase equilibrium (homogeneous equilibrium model) is employed, the denominator is taken to be a constant: it is set equal to the mean of the wellhead pressure and the pressure at the depth of vaporization. In [6], where the homogeneous equilibrium model ignoring acceleration was used, the terms in the denominator were set equal to the mean density of the mixture and mean velocity of the flow. In [7], acceleration was also ignored but the phase slip was considered and integration was carried out using a commonly used expedient: the mass flow rate versus depth dependence was assumed to be linear [8]. The approach based on analytical integration of (1) is similar to the calculation of gas-lift wells. However, in steam-water wells, thermodynamic processes, specifically, the phase transition and phase density variation, have a significant influence.

The adequacy of the model can be considerably improved by taking into account the pressure and temperature dependences of the thermodynamic parameters entering into the formulas for the shear stress and density of the mixture. Usually, the equations of state for pure water and steam on the saturation line are used. The complexity of the equations of state [9] does not allow analytical integration if formula (1).

Computerization and the related development of numerical methods made it possible to avoid analytical integration in (1) and fully give up on finding the depth of vaporization. Models began to appear aimed at solving equations of motions using both preset wellhead parameters for calculating the bottom parameters and preset bottom parameters for calculating wellhead ones.

Simple homogeneous models were first suggested by Elder [10] and Nathenson [11]. These models ignored acceleration and the enthalpy variation in the flow. Model representations were elaborated by Naimanov [12] and Droznin [13], who took into account the phase slip.

The next step toward raising the adequacy of the models is to consider the enthalpy variation, for which purpose an equation of motion, is introduced into the model. For the first time, this was done by Gould [14].