The tasks of hydraulics of steam-water wells in the development of steam-hydrothermal fields

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Abstract. Actual problems and prospects of practical development of geothermal fields are noted in the present work. The mathematical models for the calculation of flows in steam-water geothermal wells are described. The author's models cover the whole range of possible flow conditions.

1 Introduction

The use of the deep heat of the Earth is not currently an exotic direction of non-traditional energy [1, 2]. In the main provisions of the "Energy Strategy of Russia for the period up to 2020" [3], the potential ability of non-traditional energy, including geothermal, to abundantly provide domestic demand for the country is noted.

Now in Russia, five geo-power Stations with a total installed capacity of 81.2 MW are operated, three of which are located in Kamchatka (74 MW). Intensively developing geothermal energy requires improving the efficiency of the use of available resources and equipment [1, 4-6]. The prospects for the development of geothermal fields for electricity generation are obvious. In addition, geothermal fluids are a source of valuable chemical components and compounds used in balneology for heating residential and industrial premises [7, 8].

In the development of geothermal fields, unresolved problems constrain the development of this direction. They are fundamental for the appropriate stages of development of fields. The relevance of the direction as a whole determines their high practical importance. Most of these problems relate to the system of production and transportation of the heat-carrier.

Prospects for the practical development of geothermal fields are associated with deposits, the heat-carrier of which is a mixture of water and steam. Of particular importance is the need to develop reliable methods for calculating steam-water flows [9, 10], which requires appropriate scientific and methodological foundations for the calculation of steam-water flow in the wellbore.

Some of the problems relate to the measurement of flow parameters of steam-water wells. These measurements are used to calculate the reserves of the field, its development and ground equipment are designed. The difficulty lies in the need to measure two independent parameters characterizing the steam-water mixture. Traditional single-phase

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hydraulic methods are not acceptable in this case. A combination of methods or special approaches is required.

One of the important points in the development of geothermal fields is the calculation of the flow of steam-water mixture in the production wells necessary to determine the parameters in the reservoir by wellhead parameters for the calculation of reserves and reverse calculation for the design of field development.

The complexity of the processes of dynamics of the steam-water mixture, which are interrelated with thermodynamic processes, often does not allow obtaining simple solutions to the problems. Mathematical modeling of these processes helps significantly [7].

The development of modern science is impossible without mathematical modeling and computational experiment, which in some cases can reduce the number of field experiments or completely replace them. A qualitative mathematical model is usually more accessible and convenient for research than a real object. The model allows learning how to manage the object by testing different options. Mathematical modeling of steam-water flows is widely used in the development of geothermal fields for the calculation of flows in wells.

2 The development of the model assumptions

Hydraulically wells are circular vertical or inclined pipes of telescopic design. The difficulties of modeling the flow in wells are associated with the presence of steam-water flow. A wide range of rate steam content suggests the possibility of all the main structures of gas-liquid flow.

All currently known methods and models for the calculation of steam-water flows in wells the integral method for describe are use. In this method uses to describe the averaged flow parameters over the cross section of the stream. The models differ in the quantity and type of empirical dependences used to close systems of equations [7, 11].

At present, the most famous and widely used is the HOLA model, developed by G. Björnson in 1987 [12]. It based on the numerical solution of one-dimensional equations of continuity, motion, and energy. The model assumes the possibility of single-phase flow and different regimes of two-phase flow, also takes into account the phase sliding. In the same year, A. N. Shulyupin developed a model of WELL similar in ideology. Coordination of the calculated results with experimental data is presented in [13]. A significant disadvantage of the first version of the program WELL was the loading of the model and data using punch cards. Perfection and development of computer technology required modification of the program. Further study and research of the dynamics of the steam-water mixture, as well as the application of various approaches to the description of flow, led to the creation of new models based on the developed WELL.

By the end of the last century, heat transfer with surrounding rocks was taken into account when modeling the flow in wells [14]. Different researchers in their models considered only radial heat flow. Specifically for the research of the vertical component of the heat flow, the authors developed the WELL-2 model in 2005. The WELL model was taken as a basis. Heat losses in the energy equation were calculated by solving the problem of two-dimensional heat transfer with the surrounding rock in cylindrical coordinates [15]. The changes affected using equations of state. The original model was intended for the wells of the Pauzhetsky field, where the limit of up to 25 bar for the equations of state of saturated steam and water was sufficient. The new model was developed with a focus on the deeper and higher enthalpy wells of Mutnovsky field with a pressure at a depth of 100 bar. New equations of state IFPWS-IF 97 were introduced into the model [16]. This made it possible to use it for the Mutnovsky field. The developed model was used for research. The result showed that to take into account the thermal losses in the surrounding rocks it is enough to take into account the radial heat flow by means of introducing the coefficient of unsteady heat transfer [7].

Next, the quantity of considered two-phase mixture flow regimes and the criteria of their existence are changed in various modifications of the model. On the basis of the accumulated experience of developing mathematical models for calculating the flow of steam-water geothermal wells for practical problems of hydraulics, models of WELL-4 and its modification of WELL-4C, WELL-4G, WELL-4CG were developed [17].

3 Model WELL-4

The basic model of WELL-4 consider. To describe the flow in the well, stationary hydrodynamic equations are used. The flow is assumed to be quasi-stationary (i.e., over time, the heat flow on the walls, which is included in the energy equation). The basic one-dimensional equations of continuity, movement and energy were obtained using the integral method and the two-speed model for two-phase flow

$$dG = 0 , \tag{1}$$

$$\rho''\varphi v'' dv''+\rho'(1-\varphi)v' dv'+\frac{(v''-v')}{\pi R^2}Gdx = -dp - \frac{2\tau}{R}dz - (\rho''\varphi + \rho'(1-\varphi))gdz , \tag{2}$$

$$dh + gdz + de = dq , \tag{3}$$

where G – mixture mass flow rate, ρ'', ρ' – steam and water density, φ – true volumetric steam content, v'' и v' – steam and water speeds, x – mass rate steam content, p – pressure, R – radius of the well, τ – shearing stress at the wall, g – gravitational acceleration module, z – coordinate along the pipe axis oriented upwards, h – specific enthalpy of the mix, dq – change of the specific energy of the flow by means of the heat flow from the well walls. e – specific kinetic energy determined as

$$e = (xv''^2 + (1 - x)v'^2)/2. \tag{4}$$

The direction of calculations in WELL-4 is carried out from the wellhead to bottom-hole. The integration step is entered, it is possible to change the calculated diameter of the well, taking into account its telescopic construction.

The model describes single-phase (pure water) and two-phase (steam-water) flow. For two-phase flow three regimes are provided: flow with low steam content (structures with continuous liquid phase), the flow of the transition structure and the flow with a high steam content (structures with a continuous gas phase).

In the event of the flow with a minor steam content (bubble and assembly structure), the well-known formula is used for determining the speed of the steam, applied successfully for the corresponding structures

$$v'' = 1{,}2w + 0{,}35\sqrt{2gR(1-\rho''/\rho')} , \tag{5}$$

where w - reduced speed of the mix, determined also as the speed corresponding to the homogeneous model.

The emulsion structure is transient between the assembly and dispersed-ring structures, and in the event of high speeds is transient between bubble and dispersed-ring structures. This formula is used to determine the steam velocity

$$v'' = w + v_c(1 - w/v_s) , \tag{6}$$

where v_c - critical speed of the movement of saturated water and v_s - is the speed of steam determined by formula (4).

The existence of the conditions with a continuous gas phase associated with the dispersed-ring structure requires meeting two conditions.

First, the steam content should be sufficient for the formation of the flow core.

$$\beta > 0{,}8\,, \tag{7}$$

where β - volume consumed steam content.

Second, the speed in the core should be sufficient for holding the liquid film on the wall, which requires the predominance of the inertia forces of the steam core over the gravity forces; i.e., the Froude number should be above one:

$$\mathrm{Fr} > 1\,. \tag{8}$$

Moreover, the conditions in which the specified constraints were not met but the steam speed has reached the critical speeds of saturated water are considered transient.

The choice of formulas determining the true speed of one phase or the sliding factor (ratio of gas and liquid speeds) is the principle issue for the description of gas and liquid flows.

The known formula of Z.L. Miropolsky is used to determine the slip coefficient in the dispersion-ring flow

$$s = 1 + \frac{13{,}5\,(1 - p/p^*)(1 - \mathrm{M}^2)}{\mathrm{Fr}^{5/12}\,\mathrm{Re}^{1/6}}\,, \tag{9}$$

where s - sliding factor, Fr, Re and M - the Froude, Reynolds, and Mach numbers, p^* - pressure at the critical point ($22{,}115 \cdot 10^6$ Pa).

Determining the shearing stress at the pipe wall is also important. In the proposed model, the following formula is used for all conditions of the two-phase flow:

$$\tau = \xi(\rho'' v''^2 \varphi + \rho' v'^2 (1 - \varphi))/8\,, \tag{10}$$

where ξ - coefficient of friction.

The following formula [7] is recommended for determining changes in the specific energy of the flow.

$$dq = \frac{-\Delta T(z) 2\pi\lambda}{G \ln(1 + \sqrt{\pi a t / R^2})} \tag{11}$$

where $\Delta T(z)$ - difference in the current temperature of the heat carrier and its initial temperature equal to the temperature of the rock massif at the infinite border, λ - coefficient of heat conductivity of the surrounding rocks, t - is the time from the beginning of the operation of the well, a - conductivity temperature of the surrounding rocks.

4 Practical use

To substantiate the project for reconstruction of the A-2 well of the Mutnovsky geothermal field, the forecast of this well's performance was performed using the WELL-4 model. The planned reconstruction was to be installed from the mouth to a depth of 1200 m inside the existing casing with an internal diameter of 0.225 m of the liner with an internal diameter of 0.16 m. By the computer program WELL-4, according to the measurement of flow parameters at various stages of wellhead pressure, the pressure at a depth of 1200 m was determined with the existing wellhead design. Then, using the inverse calculation, the wellhead pressure was calculated at the new inner diameter. The result of the reconstruction confirmed the predictions [18], which is a confirmation of the model's effectiveness in the conditions of the Mutnovsky field.

5 Modification of the WELL-4

All known models are based on the equations assuming the invariability of the mass flow of the heat carrier along the flow channel, these recommendations are correct only until the border of the feed zones, below which the rate changes.

The thermal aquifer sequence of Russian geothermal fields consists of rocks characterized by fracture- vein-type permeability. In the process of drilling the well intersects 1 to 7 feed zones 1 to 300 m thick. The wellbore in the feed area consists of pipes, the walls of which are perforated for fluid supply from the thermal aquifer sequence. In some wells drilled at the stage of field exploration and the wells being operated, the supply occurs through the uncased part of the wellbore.

The WELL-4G model was developed for the calculation of flows in the feed area based on WELL-4 [17]. The well feed is modeled as one zone stretched from the upper border of the feed zones to their lower border. It was supposed to be a linear change in the flow rate with depth. In this case, the equations of continuity, motion, and energy have the form

$$dG = (G/L)dz \,, \quad (12)$$

$$\rho''\varphi v''dv''+\rho'(1-\varphi)v'dv'+\frac{(v''-v')}{\pi R^2}Gdx+\frac{(v''x+v'(1-x))}{\pi R^2}dG = \\ = -dp-\frac{2\tau}{R}dz-(\rho''\varphi+\rho'(1-\varphi))gdz \,, \quad (13)$$

$$dh + gdz + de + edG/G = 0 \,, \quad (14)$$

where L – thickness of the feed area.

In the case of nonlinearity of the flow rate change with depth in the feed zone, instead of (12), another dependence can be introduced without changing the rest. Other calculation formulas are taken from WELL-4.

This model was realized in the same way as WELL-4, with a slight change in the input block. In particular, one of the initial values is the current specific enthalpy of the mixture. In the base model, the initial value was almost the measured specific enthalpy of the inhibited flow of the mixture, which required an additional unit to calculate the current enthalpy at the wellhead. It is logical to use the new model together with the previous model: make a calculation from the well- head to the upper border of the feed zones with the WELL-4 model, and make the calculations below it with the WELL-4G model.

Table 1 presents information on operating the wells 24, 042, 037 Mutnovsky field parameters.

Table 1 The main characteristics of the wells of the Mutnovsky field

Well	Wellhead pressure, bar	Flow rate, kg/s	Mix enthalpy, KJ/kg	Deph, m	Feed zone, m
024	7,9	15,5	1020	1300	1000-1300
042	8,4	69,9	1200	1860	1355-1837
037	9,6	21,5	1200	1771	1339-1669

Figure 1 shows the calculated pressure profiles in the functioning wells 24, 042 and 037 of the Mutnovsky field of steam hydrotherm.

Points A in the curves correspond to the upper border of the feed zone. Points B correspond to a transfer from the single-phase current to the two-phase one.

- Well 24: in the feed zone the heat-carrier is in the single-phase (point B in the curve is above point A).
- Well 042: in the feed zone, there are both sections with single-phase (below point B) and dual-phase flows (the section from A to B).
- Well 037: in the feed zone the heat-carrier is in the double-phase (there is no point B in the curve).

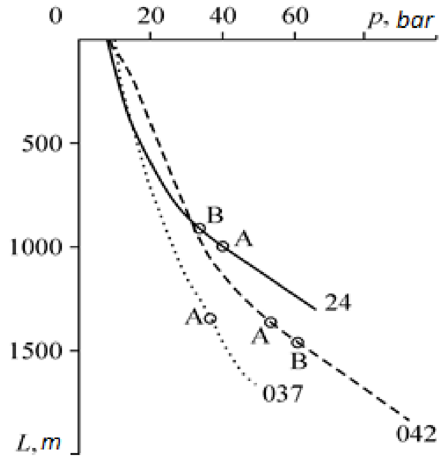

Fig. 1. Calculated distribution of pressure in depth in operating wells 24, 042, and 037 of the Mutnovsky steam hydrothermal field.

Determination of the pressure profile in the bore of the operating well intersecting the feed zone and its comparison with the data of stationary conditions will allow for studying the filtration flows in the bottom-hole zone having a significant impact on well productivity.

Directional drilling is actively used today to improve the efficiency of the intersection of the productive aquifer. The structure of the slant well consists of three sections: the upper vertical, middle deviated (with the set change of the inclination angle), and lower inclined (with a constant inclination angle). The WELL-4C [19] is based on the WELL-4 model and is designed for the calculation of flows in slant wells.

In Eqs. (2) and (3) introduced amendment: module of gravitational acceleration is multiplicatied on the cosine of the well deviation angle from the vertical. Respectively, a package responsible for determining the specified angle is introduced in the implementation of the model in the software.

The WELL-4GC is based on the model WELL-4G and is designed for the calculation of the flows in the feed area of the slant wells. In Eqs. (13) and (14) introduced amendment: module of gravitational acceleration is multiplicatied on the cosine of the well deviation angle from the vertical. The tilt angle is constant and in the implementation of the model is entered in the source data. The other formulas and dependences are identical to WELL-4 G.

Thus, to calculate flow in the feed zone vertical steam-water wells developed a model of WELL-4G. To calculate steam-water flows in inclined wells at constant mass flow rate is proposed model WELL-4C. To calculate in the feed zone inclined steam-water wells is proposed model WELL-4GC.

6 Conclusion

In the present work, existing problems, approaches and methods used in modeling steam-water flow in geothermal wells are investigated. The described WELL-4 computer program developed and implemented by the authors and the WELL-4-G (with variable flow) modifications, WELL-4-C (with the possibility of insertion into the inclined section and the previous section with a set angle) WELL-4-GC allow to cover the full range of possible tasks associated with the calculation of flow in wells in the development of steam-hydrothermal field.

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