Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Simulators for Steam-Water Flow in Geothermal Wells and Pipelines

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Keywords: steam-water flow, geothermal well, pipeline, mathematical model, simulator.

ABSTRACT

Mathematical models and simulators using for investigation of steam-water flow in geothermal wells and pipelines in Russia are described. Needed conditions in order to use the simulators are determined. Practical problems solved by the simulators are described. New problems for steam-water flow simulation at geothermal field development are noted.

1. INTRODUCTION

Practically all spheres of human activity are carried out at the expense of energy consumption. The resource limitations of traditional fuels and the necessity of finding environmentally friendly methods of producing energy, creates the need to attract alternative sources of energy. These sources include geothermal resources. Over the years, there has been a steady increase in the involvement of geothermal resources in the global economy. More than 80 countries use geothermal resources as a direct source of energy in heating systems, heat pumps, balneological basins, etc. (Lund and Boyd, 2016). More than 20 countries produce electric power from geothermal sources (Bertani, 2016). There are five geothermal power plants (GeoPP) operating in Russia, three of which are located in Kamchatka. The source of heat-carrier for GeoPP is high-temperature steam-hydrothermal fields, the production wells of which bring the steam-water mixture to the surface. The presence of heat-carrier in the two-phase state determines the relevance of a wide range of problems. Most of them relate to the system of extraction and transportation of heat-carrier. At the same time, the need to develop reliable methods for calculating steam-water flows in production wells and surface pipelines is of particular importance (Dobrokhotov and Povarov, 2003; Chermoshentseva and Shulyupin, 2011; Shulyupin and Chernev, 2012).

The difficulty of the processes of steam-water mixture dynamics often does not allow obtaining simple solutions to the problems. At the same time, mathematical modeling of the involved processes can help substantially (Chermoshentseva and Shulyupin, 2011). The development of modern science is impossible without the use of mathematical modeling and computational experiment, which in some cases can reduce the quantity of field experiments or even replace them. A well-constructed mathematical model is usually more accessible and convenient for research. The model allows to learn and properly manage an object by testing various options. Mathematical modeling of steam-water flows has become widespread in the development and exploitation of geothermal fields.

2. CALCULATION OF FLOWS IN STEAM-WATER WELLS

The existing approaches and methods of development of models for the calculation of flows in steam-water wells are considered in (Chermoshentseva and Shulyupin, 2011; Shulyupin and Chermoshentseva, 2013). All of them use the integral method, taking averaged parameters in section of the flow to describe it. The models differ in the quantity and type of empirical dependencies used to close systems of equations.

In 1987, for the Kamchatka Department of Use the Deep Heat of the Earth, Shulyupin A.N. developed a model WELL. The model is based on the numerical solution of one-dimensional equations of continuity, motion and energy with the ability to calculate the single-phase flow and various modes of two-phase flow regimes taking into account the sliding phase. The model gave a satisfactory agreement between the calculated results and the experimental data (Shulyupin, 1991). A significant disadvantage of the program was loading models and data using punch cards. Improvement and development of computer technology required modification of the program. Further research and analysis of the dynamics of the steam-water mixture, use of various approaches to the description of flows, led to the creation of new models based on WELL.

As a result of joint work, Shulyupin A.N. and Chermoshentseva A.A. created various modifications of the model WELL. The quantity of considered flow regimes of a two-phase mixture changed, various criteria for their existence were introduced, two-dimensional heat exchange with surrounding rocks was taken into account (Chermoshentseva, 2006), the equations of state of saturated steam and water changed, due to the expansion of the range of thermodynamic conditions of developed fields, an attempt was made to apply a structural approach (Shulyupin and Chermoshentseva, 1998).

During the work on the justification of the reconstruction of the well A-2 of Mutnovsky field (2011), the WELL-4 model was created (Shulyupin and Chermoshentseva, 2013), and then on its basis a set of models that allows covering the whole range of possible tasks related to the calculation of flows in wells in the development of steam-hydrothermal fields. Taking into account modern trends in the evolution of technologies during the development of steam-hydrothermal fields, in 2018 the complex program WELL-4 was expanded. The authors created and realized a mathematical model WELL-4z for calculating quasi-stationary flows in steam-water wells in individual zone of the feeding aquifer.

3. BRIEF DESCRIPTION OF THE COMPLEX OF MATHEMATICAL MODELS WELL-4

The basic model WELL-4 is designed to calculate the flow in a vertical well above the feeding aquifer. A quasi-stationary flow and unchanged mass flow rate along the channel length are allowed. The model includes the possibility of a single-phase (water) flow and a two-phase (steam-water) flow, which are divided into three regimes: low steam quality, high and transient. The equations of state for the pressure in the steam flow 100 bar (Alexandrov, 1998) are used. Telescopic construction of the well and possibility of heat exchange with the surrounding rocks are taken into account.

The thermal aquifer complex of Russian geothermal fields consists of rocks characterized by fracture- and 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 as well as during field operation, the supply occurs through the uncased part of the wellbore

To study the features of the interaction of the well with the feeding aquifer in 2014, the model WELL-4G (Shulyupin and Chermoshentseva, 2015) was created, describing the flow in a vertical well in the feeding section. The aquifer was considered to consist of one feeding zone, in which the mass flow rate varies linearly from zero at the lower boundary to the maximum value namely the current value at the wellhead. It required adjustments to the equations of continuity, motion and energy to account for changes in mass flow rate.

Active use of inclined drilling technology required the creation of mathematical models for inclined wells in the feeding zone (WELL-4) and outside it (WELL-4G). Inclined wells have three sections: the upper vertical, the middle with a set of angle of inclination and the lower with a constant angle of inclination. For calculations in the middle and lower parts of the well, gravitational terms of the equations of motion and energy, the gravitational acceleration modulus is multiplied by the cosine of the angle of deviation of the borehole axis from the vertical.

Some foreign models, such as HOLA (Bjornsson, 1987) and FloWell (Gudmundsdottir and Jonsson, 2015), allow changing the mass flow rate along the wellbore as it passes through the feeding zones. In this case, the flow in the zone itself is not modeled (a discrete flow change is assumed). In the presence of zones 100 m or more, this is a significant disadvantage. This fact prompted us to create a model devoid of the deficit of these foreign analogs, capable of calculating flow parameters in the individual zone of the feeding aquifer. The relevance of the development of such a model is also determined by the fact that, depending on the technology of the excitation of the well, various options for combining the active feeding zones can be implemented (Shulyupin, 2018). The ability to calculate flow parameters within the zone will allow optimization of the excitation technology.

The basis of the new model WELL-4z is advisable to take the model WELL-4GC, taking into account the changing flow with depth. In this case, it is necessary to assume a linear change of the flow along the length of the feeding aquifer from the input value to the output value from the zone. Thus, the system of basic equations (continuity, motion and energy) of the model looks like this:

$$dG = \frac{(G_2 - G_1)}{L} dz \,, \tag{1}$$

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

$$dh + de - g_z dz = 0 \,, \tag{3}$$

where G and G'' are the mass flow rate of mixture and steam, G_1 and G_2 are the mass flow rate of mixture in well at the level of the lower and upper boundaries of the zone, L is length of the zone, R is the radius of the well, ρ'' and ρ' are the steam and water density; φ is void fraction, v'' and v' are the velocity of steam and water, z is the coordinate along the pipe axis oriented upwards, p is the pressure, τ_c is the shearing stress at the wall of well, ρ is the mixture density, g_z is the projection of the vector of the gravitational acceleration on z (for vertical pipe $g_z = -g$, for the inclined $g_z = -g\cos\alpha$, where α is the angle of inclination from the vertical axis), h is the specific enthalpy of the mixture, e is the specific kinetic energy.

4. PROBLEMS OF TRANSPORTATION OF STEAM-WATER MIXTURE

At the beginning of the development of the steam-hydrothermal fields, a separate scheme for transporting the heat-carrier was widely used. Separation was carried out near the wellhead. Steam was supplied via pipelines to the plant and water was discharged. The tightening of environmental requirements and the widespread introduction of return injection to maintain reservoir pressure have led to the need joint transportation of steam and water to a common place of use. In this connection, at the end of the last century, a two-phase transportation scheme began to be actively introduced. Interest in two-phase transportation continues to this day (Ghaderi, 2010; Rizaldy and Zarrouk, 2016; Garcia-Gutierrez et al., 2015; Cheik and Ali, 2015). Operation of pipelines of steam-water mixture revealed two main problems: unstable regimes emerging of the low transport velocity, and a significant hydraulic resistance, which is characteristic for high velocity transportation. Therefore, at the design stage of pipelines there was a problem of choosing the optimal diameter, which, on the one hand, would provide minimal hydraulic losses and, on the other hand, would ensure a stable mode of transportation. There was also a methodological problem to determine the dependence of the flow rate of wells from the wellhead pressure. There is very little information about specific ways to solve these problems in world practice. For the calculation of steam-water mixture pipelines in domestic fields, A.N. Shulyupin and A.A. Chermoshentseva created a computer program MODEL (Chermoshentseva and Shulyupin, 2011).

Initially, the program was conceived as a simplified version of a larger product based on a complex model of a dispersed annular-mist flow (Shulyupin and Chermoshentseva, 1998). The first pipelines at Mutnovskaya GeoPP were constructed without proper calculation. After commissioning, there were problems. Emergency calculations carried out by the program revealed its sufficient accuracy. This fact and ease of use predetermined its widespread use. The program calculates the pressure drop by the value of the parameters at one nodal point. It is applied for short pipes. Long pipes should be segmented into short (up to 200 m) calculated sections. The parameters of the state are determined by the equations IFPWS-IF 97 (Alexandrov, 1998). Hydraulic calculation is oriented on the annular-mist flow regime. For the calculating section of the program conforms the two-phase flow quality to the principle possibility of sustainable transportation by criterion:

$$x > \frac{1}{1 + 1.6\sqrt{\rho'/\rho''}} \quad (4)$$

where x is the two-phase flow quality.

Introduction of recommendations on the choice of the diameter of the pipes used provides a pulsation-free regime of the pipeline functional:

$$D \leq 0.278\ (G/\rho_h)^{0.4}, \quad (5)$$

where D is the diameter of the pipe, ρ_h is the density of the mixture, determined by the homogeneous model.

The total pressure drop takes into account the pressure drop due to friction Δp_f and the total pressure drop due to the local resistances Δp_m. The frictional pressure drop is calculated by the formula obtained as a simplified generalization of the results of the numerical implementation of the annular-mist flow model (Shulyupin and Chermoshentseva, 1998).

$$\Delta p_f = 0.01\rho(v_h - v_b)^2 L / D, \quad (6)$$

where v_h is the velocity of mixture on homogeneous model, v_b is the velocity of movement of the friction surface, equal to the critical velocity of movement of saturated water.

To calculate the pressure drop due to the local resistances Δp_m the formula was used:

$$\Delta p_m = 0.7\zeta\rho_h v_h^2, \quad (7)$$

where ζ is the total coefficient of local resistance, defined as for a single-phase flow.

Usually, the pressure at the inlet to a group plant separator is set as a constant parameter. Flow parameters of the mixture depend on the wellhead pressure. Practice has shown that finding a solution taking into account the influence of wellhead pressure is the most convenient graphical method. According to the well performance curve showing the dependence of the flow rate on the wellhead pressure, using the pipeline calculations, a well-pipeline system performance curve is plotted showing the dependence of the flow rate on the outlet pressure from the pipeline (Shulyupin, 2011). Using the MODEL program, most of the existing pipelines at the Mutnovsky field (Shulyupin, 2011) were calculated. Many pipeline modifications were carried out reasonably. The calculation of two pipelines at the Pauzhetsky field was performed. In all cases, projected estimates of pressure drops and flow rate were confirmed.

Rizaldy and Zarrouk (2016) presents calculations of the pressure drop due to friction with experimental data obtained at the geothermal field Lahendong, Indonesia for horizontal pipes with a diameter of 10-22 inches (0.254– 0.559 m). The calculations were performed only taking into account the difference in friction. It is noted that in the experimental data the main behavior is the annular-mist flow regime, the homogeneous model gives one of the most appropriate comparisons to the experiments, especially for large diameter pipes. Note that formula (6) is also one of the most appropriate to the classical homogeneous model. Only a correction for the velocity of the friction surface is introduced. In formula (6), the coefficient of friction is taken as 0.02. In (Rizaldy and Zarrouk, 2016) there are no clear recommendations for determining the friction coefficient, but it is indicated that it depends on roughness. That is, the calculated pressure drop for large diameter pipes according to the recommendations (Rizaldy and Zarrouk, 2016) is reduced due to the friction coefficient, and in the formula (6) due to the correction for the velocity of the friction surface. Thus, it can be argued that the recommendations for the calculations proposed in the MODEL are consistent not only with domestic experience, but do not contradict the experimental data presented in (Rizaldy and Zarrouk, 2016).

5. CONCLUSIONS

1. The evolution of technologies in the development of steam and hydrothermal fields indicates the need to develop a mathematical model for calculating quasi-stationary flows in steam and water wells in the individual zone of the feeding aquifer. This problem has been solved by WELL-4z model.

2. The whole range of tasks related to the calculation of a quasi-stationary flow in a production steam-and-water well during the development of steam-hydrothermal fields can be covered by two models: WELL-4C for calculating the flow from the wellhead to the feeding aquifer, WELL-4z - the individual zone of the feeding aquifer, allows us to calculate the flow parameters inside the zone, in contrast to foreign analogues.

3. Despite the active development of steam-hydrothermal fields in the world, today there is not enough information in the world open sources about the methods of calculating the systems of two-phase transportation of the heat carrier. Fragmentary information indicates that the existing methodologies are suited for high flow velocity, characterizing of the annular-mist regime, and are aimed mainly at calculating pressure drop due to friction.

4. The computer program MODEL has positive practical application experience for the calculation of pipelines of a steam-water mixture during the development of domestic steam-hydrothermal fields.

REFERENCES

Alexandrov, A.A.: The IAPWS-IF97 Formulation for the Thermodynamic Properties of Water and Steam for Industrial Use. Part I: Basic Equations, *Therm. Eng.*, **9**. (1998), 69-77. [in Russian].

Bertani, R.: Geothermal Power Generation in the World 2010–2014 Update Report, *Geothermics*, **60**, (2016), 31-43. doi:10.1016/j.geothermics.2015.11.003.

Bjornsson, G.: A Multy-Feedzone Geothermal Wellbore Simulator. *Report LBL-23546*. Lowrence Berkeley Laboratory, (1987).

Cheik, H.S., and Ali, H.A.: Prefeasibility Design of Single Flash in Asal Geothermal Power Plant 2x25 MW, Djibouti, *Proceedings,* World Geothermal Congress 2015, Melbourne, Australia, (2015).

Chermoshentseva, A.A.: Heat Carrier Flow in a Geothermal Well, *Mathematical Modeling*, **18**. (2006), 61-76. [in Russian]

Chermoshentseva, A.A., and Shulyupin A.N.: Mathematical Modeling of Steam-Water Flows in Elements of Geothermal Well Equipment. Petropavlovsk-Kamchatsky: KamchatGTU, (2011), 144 p. [in Russian]

Dobrokhotov, V.I., and Povarov, O.A.: Use of Geothermal Resources in Power Engineering of Russia, *Heat Power Engineering*, **1**, (2003), 2-11. [in Russian]

Garcia-Gutierrez, A., Martinez-Estrella, J.I., Ovando-Castelar, R., Vazquez-Sandoval A., and Rosales-López, C.: Thermal Efficiency of the Los Humeros Geothermal Field Fluid Transportation Network, *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia, (2015).

Ghaderi, I.: Comprehensive Comparison Between Transmission Two-Phase Flow in One Line and Two Line Separately For 50 MWe Power Plant in Sabalan, Iran, *Proceedings*, World Geothermal Congress. Bali, Indonesia, (2010).

Gudmundsdottir, H., and Jonsson, M.T.: The Wellbore Simulator FloWell – Model Enhancement and Verification, *Proceedings,* World Geothermal Congress, Melbourne, Australia. (2015).

Lund, J.W., and Boyd, T.L.: Direct Utilization of Geothermal Energy 2015 Worldwide Review, *Geothermics*, **60**, (2016), 66-93. doi:10.1016/j.geothermics.2015.11.004.

Rizaldy, and Zarrouk, S.J.: Pressure Drop in Large Diameter Geothermal Two-Phase Pipelines, *Proceedings*, 38th New Zealand Geothermal Workshop. New Zealand, (2016).

Shulyupin, A.N., and Chermoshentseva, A.A.: Model of Annular-Mist Flow in Geothermal Wells, *Dynamics of Heterogeneous Environment in the Geo-Technological Production*. Petropavlovsk-Kamchatsky: KGRAF, (1998), 23-35. [in Russian]

Shulyupin, A.N., and Chermoshentseva, A.A.: On Calculation of a Steam-Water Flow in a Geothermal Well, *Technical Physics*, **58**, (2013), 1100-1105.

Shulyupin, A.N., and Chermoshentseva, A.A.: Steam-Water Flow in a Geothermal Well, *Thermophysics and Aeromechanics,* **4**, (2015), 475-480.

Shulyupin, A.N., and Chernev, I.I.: Problems and Prospects of Development of Geothermal Resources of Kamchatka, *Georesources*, **1(43)**, (2012), 19-21. [in Russian]

Shulyupin, A.N.: Flow in a Geothermal Well: Model and Experiment, *Volcanology and Seismology*, **4,** (1991), 25-31. [in Russian]

Shulyupin, A.N.: Problems of Hydraulics of Steam-Water Mixture in the Development of Geothermal Fields. Vladivostok: Dalnauka, (2011), 262 p. [in Russian]

Shulyupin, A.N.: The Stability of the Regime of Operation of the Steam-Water Wells. Khabarovsk: «Amurprint», (2018), 136 p. [in Russian]