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FLOW INSTABILITY IN PRODUCING WELL AT FLASH-STEAM FIELDS

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Theoretical foundations are presented for forecasting operation instability of producing wells at flash-steam fields. The considered topic gains actuality because of the new conditions for developing geothermal power industry which call for solicitous use of the wells fund. Instability mechanism is considered: increased discharge results in the growth of the force generating the flow, which in turn results in still higher discharge. The force grows due to weakening of gravitational component which counteracts the flow in the result of depletion in the density of flash-steam mixture. It is demonstrated that due to the specifics of development of such instability in a geothermal well the reaction of well foot pressure to change in the discharge cannot influence the stability in any effective way, while the reaction of wellhead pressure may work as a stabilizing factor. Principal weaknesses are pointed out of former ideas on flow instability in flash-steam wells. The condition of stable flow should be the positive value of the derivative on discharge of the internal well foot pressure defined as the sum of wellhead and internal pressure drop.

Key words: flash-steam flow, stability, geothermal well, seam.

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Introduction. Terrestrial heat is one of the renewable energy sources with which they associate the solution of the global energy problem in the future and stable growth of its consumption in the present [11, 14]. Modern geothermal power industry is now at the stage of proceeding to zero-subsidizing development [5]. This explains the topicality of questions related to increasing the efficiency of use of the available technical resources, including the fund of wells, the expenses on drilling them constituting a major part of every project.

Lately a lot of attention is paid to the issue of well stimulation, as indicated by the large number of publications on that topic, see [10, 12, 16, 20], etc. So far the problem of flow stability in flash-steam wells has not won proper attention, such wells being the main provider of heat carrier for geothermal power plants. Meanwhile ways have been found experimentally to achieve stable operation of the wells that were believed to be unfit for exploitation before [19]. To update the means already known and develop the new ones it is needed to study the mechanisms maintaining flow stability in the wells.

Theoretical ideas on flow stability in flash-steam wells are laid down in studies by V.A. Droznin [1-3]; these are based on the mechanism of maintaining stability proposed in the study by V.M. Entov [4]. It is demonstrated however in [9] that representations according to which a stable flow is possible with two different discharges while the conditions at wellhead remain the same deviate from the practical data. Therefore there is a need to develop a theory of stable flash-steam flow in a geothermal well that would not be in contradiction with the available experimental data.

Theoretical foundations of stable flow in a flash-steam well. To understand the processes resulting in generation and development of instability, consider the motion of an element in the channel between cross sections distanced by Δz from each other. Using the second law of Newton for that element we may write its equation of motion in the projections to the axis z:

$$\frac{\partial j}{\partial t} = \frac{p_1}{\Delta z} - \frac{p_2}{\Delta z} - f_f - f_c - f_g , \qquad (1)$$

where j is specific mass discharge; p_1 and p_2 are external pressures at the upper and lower cross sections of the element, respectively; f_f is the force of internal friction per unit volume; f_c is the force of inertia per unit volume, related to convective acceleration; f_g is the gravitational force per unit volume.

Lefthand part of equation (1) characterizes thee non-stationary part of change of impulse while the righthand part expresses the sum of forces acting on the element. In case the perturbation in the form of increasing impulse (or the specific mass discharge) increases the righthand part of that equation, the total force causing the increase of impulse grows too. Therefore an increase of impulse would result in the increase of moving force which would increase the impulse in its turn. Hence, such a perturbation would disrupt the flow stability. If an increase of discharge lowers the total force, which may be treated as the growth of forces preventing the increase of impulse, such a perturbation will find no further development.

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Formalizing the described mechanism let us define the condition of stability as the negative value of partial derivative of the righthand part of the equation (1) over discharge. Having expressed the sum of forces $(f_f + f_c + f_g) = = \Delta p_{int}/\Delta z$, where Δp_{int} is the internal pressure drop (or the sum of such drops due to friction, convective acceleration and gravitation), we may write stability condition as

$$\frac{\partial \Delta p_{\text{int}}}{\partial j} > \frac{\partial}{\partial j}(p_1 - p_2). \qquad (2)$$

The well is usually presented as a vertical pipe; in rarer cases it features some complex geometry with a vertical upper part and an inclined lower part. Let us consider the stability of the well as a whole, when the length of the considered element Δz is equal to the well length. Then p_1 is the well foot pressure, p_2 is the wellhead pressure. Note that in (2) these parameters are treated as external, i.e. they are defined by the conditions of the flow in the bed feeding the well and the conditions in the system of transporting heat carrier from the wellhead. In the actual conditions the righthand part condition (2) is always less than zero for the well as a whole. Condition (2) may be violated in case its lefthand part becomes negative.

The dependence was analyzed of the internal drop of pressure on discharge for a typical producing well in Pauzhet flash-steam field, Kamchatka (Fig. 1). The internal pressure drop was calculated using the WELL-4 model [7]. The figure presents the dependence of the external pressure drop on discharge ($\Delta p_{ext} = p_1 - p_2$) for constant p_2 and a linear dependence of p_1. Meanwhile thee wellhead pressure is defined by pressure in the main pipeline and does not depend on discharge in practical terms. The dependence of p_1 corresponds to the stationary inflow from the bed (line inclination and the position of the initial point correspond to those typical for the conditions at that field). The working point sits at the lines crossing. Point 2 corresponds, and point 1 does not correspond to condition (2).

The effect of friction force and inertia increases due to convective acceleration for higher discharge. With the discharge growing phases start to mix more, which results in a lower ratio of their average velocities and lower density of the mixture, the gravity force also lowering. It was proven experimentally that at low discharges the average velocities of steam and water may even have different directions [17]. Hence, the disruption of condition (2) may manifest itself when the effect of friction and acceleration is weak. In this particular case for instability to manifest itself the force of gravitation is defining while phase transformation during decompression may be a strengthening factor that lowers the mixture density even more. That case may be classified as gravitational instability.

Relationship (2) coincides with the condition belonging to the Ledinegg class of instability [13, 18]. However, it is difficult to associate he considered phenomenon with that class. First the traditional Ledinegg instability is related to the particular features of friction and phase transformation generated by the heat flux on the channel wall [13]. In our case neither friction nor thermal flux at the wall serve as defining factors. Second, the typical indicator of Ledinegg instability is the N-shaped profile of the dependence of internal pressure drop on discharge [18]. In our case that dependence demonstrates a V-shaped profile (Fig. 1). Commonality of the formal expression for stability conditions expresses commonality in the development of instability mechanism. Increasing (depleting) the impulse results in the increase (drop off) of the force that results in still further increase (drop off) of the impulse, etc.

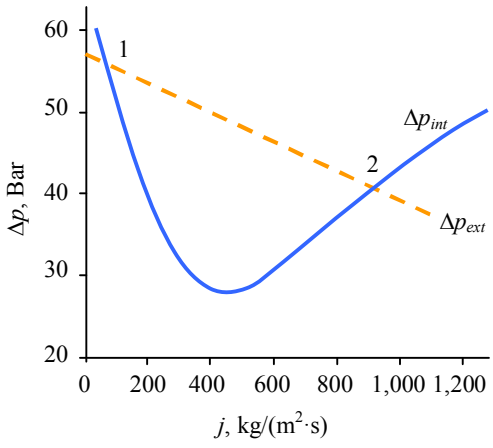


Fig. 1. The dependence of internal and external pressure drops on discharge for a typical well of the Pauzhet field flash-steam

Accounting for the fact that the righthand part of the relationship (2) is always negative for a geothermal well, a sufficient condition of flow stability should be assumed to be the positive value of lefthand part of that relationship. Theoretically, a stable flow is possible even for the negative value of lefthand part. To meet condition (2) at the expense of righthand part requires quite a fast external reaction of well foot and wellhead pressures to change in the discharge, and that is not always realizable.

Consider the possibility to deter the development of instability due to reaction of well foot pressure. Discharge fluctuations that launch instability mechanism may occur both at extreme points of the well (head and foot), and along the well

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length. The key instability factor in our case is a decrease in the mass of the mixture present in the well when the discharge increases. Fluctuations in the discharge along some stretch inside the well will not change the total mass of mixture in the well, provided discharge at the foot remains constant and equal to the discharge at wellhead. In case of internal instability such fluctuations form trains similar to those described in study [6] which differ from the rest of mass in flow parameters, and these prevent further development of instability. But these processes do not influence the stability of flow in the well as a whole. Increase of discharge at the foot of the well will result in larger total mass of mixture in the well. It is only the growth in discharge at the wellhead that is capable to deplete the total mass of mixture and launch the mechanism of gravitational instability.

Fluctuations in the discharge at the wellhead change the mass of mixture in the well. Prerequisites thus appear for the development of instability up through the flow (down the well). Note that the rate of propagation of perturbations the steam and water mixture is considerably lower than similar rates in both water and steam. For the reaction in well foot pressure to be able to influence the development of instability, perturbation from the wellhead must reach the well bottom. Geothermal well depths often exceed 2,000 m. There is a certain interval of a few dozen seconds length when the development of instability remains automodel with respect to the conditions at the well foot. Therefore, the reaction of foot pressure to changes in the discharge should not be considered as a factor capable of maintaining flow stability.

The situation with the wellhead pressure is quite different. In accordance with the reviewed mechanism it is the presence of a barrier for the development of instability in the upper part of the well that is capable of providing flow stability. Moreover, it is technically not difficult to provide the necessary rate of reaction of wellhead pressure to the change in discharge, e.g. building hydraulic resistances in the system for transporting the mixture from the well in the immediate vicinity of the wellhead. Hence the condition of stability of the flow in the steam-flash geothermal well should be used in practice in the form

$$\frac{\partial \Delta p_{\text{int}}}{\partial j} + \frac{\partial p_2}{\partial j} > 0\,. \qquad (3)$$

Condition (3) does not assume any effect on stability of the derivative of well foot pressure. Meanwhile bottomhole pressure is defined as a characteristic of the external force, in other words it is defined by the conditions in the feeding bed. Practically though well-foot pressure may be defined as an internal parameter for the well, as it is the sum of the wellhead and internal pressure drop. In that context the righthand part of the condition (3) holds the derivative of specifically the well foot pressure, of the internal well foot pressure to be more exact. Therefore the condition of stability may be defined as the positive value of the derivative of the internal well foot pressure over discharge.

Discussion of the foundations of stable flow in a flash-steam well. Note that the approach pursued in the current study, when meeting the condition (2) is considered necessary (but not sufficient) contradicts the ideas on stability that have been dominating for many years, developed in the studies by V.M. Entov [4] and V.A. Droznin [3]. In particular, it was believed earlier that a sable state is possible while condition (2) is not observed, namely, when both part of it are negative and the module of the lefthand part is larger than the module of the righthand part (point 1 in Fig. 1). The cause for adopting that solution was the desire to explain the inversion of productivity plots which express the dependence of discharge on wellhead pressure.

The inversion of productivity dependence plots is not observed in every well or every field, so not everybody considers that a veracious phenomenon. For example, all the producing wells of the Mutnovskoye field (Kamchatka, Russia) demonstrate a monotonous growth of discharge with lowering wellhead pressure [8]. As noted in publication [15], the typical productivity plot has no inversion. However, the phenomenon of inversion still exists. In 2013 the author has tested the wells of the Pauzhet field that feed the Pauzhet hydrothermal power plant with heat carrier. The purpose of the test was to identify the workable part of the productivity graph in the range of working wellhead pressure. Further on

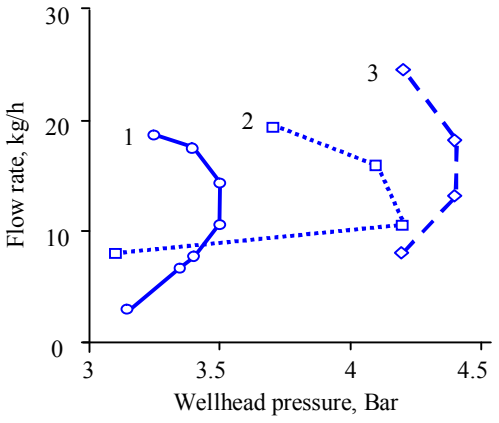


Fig. 2. Well productivity plots for the Pauzhet field
1 – well 108; 2 – well 120; 3 – well 123

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these data were used to assess the changes in well discharge in case the heat carrier transportation system would be modified; in other words, no specific task was set to detect the inversion. However, the inversion was detected in those three cases when the onversion pressure appeared to be close to the working pressure. Productivity plots for these three wells are presented in Fig. 2. Possibly, other wells feature inversions in their productivity graphs, but these were not tested for the corresponding wellhead pressures and discharge levels. Note too, that against the expectations, no principal changes in the character of discharge and pressure variations around the inversion point were observed.

In case of an inversion there are two values of discharge that may correspond to one and the same value of wellhead pressure. The simplest explanation of this fact seems to be the assumption hat a stable flow exists in both points 2 and 1, see Fig. 1, used in theoretical ideas of V.M. Entov and V.A. Droznin. In their studies the role was overestimated of the dynamics of well foot pressure while the reaction of wellhead pressure was disregarded completely. As demonstrated in study [9], it is impossible to explain adequately all the features of interlink between the wellhead pressure and discharge, basing on these ideas. However, accounting for the reaction of wellhead pressure makes it possible to interpret adequately all the types of productivity plots, including the graphs with inversion, while assuming a single possible value of discharge only for the conditions prescribed at the wellhead, which corresponds to point 2 in Fig. 1. Wellhead pressure being the same, and discharge conditions - different, the dependences of wellhead pressure on discharge should be different too.

If one considers flow stability along a local stretch as a possibility to retain external pressures, then the respective condition will be formalized as a positive value of righthand value of (2), or in its dimensionless form

$$a > 0, \tag{4}$$

where a is a dimensionless parameter of internal stability, and

$$a = \frac{j}{(\partial p / \partial z)} \frac{\partial}{\partial j} \left(\frac{\partial p}{\partial z} \right).$$

In real environment meeting the condition (4) at every stretch of the well remains problematic. In case boiling starts in the bed, that condition will be violated along the feeding line where the discharge changes from its working value at the top boundary to zero at its bottom boundary. In actual wells the length of feeding line is a few dozen meters, sometimes exceeding a hundred meters [7]. In case the level of the start of boiling is somewhere within the well then disagreement with the condition set is possible for low steam content when the effect of friction and convective acceleration is minor.

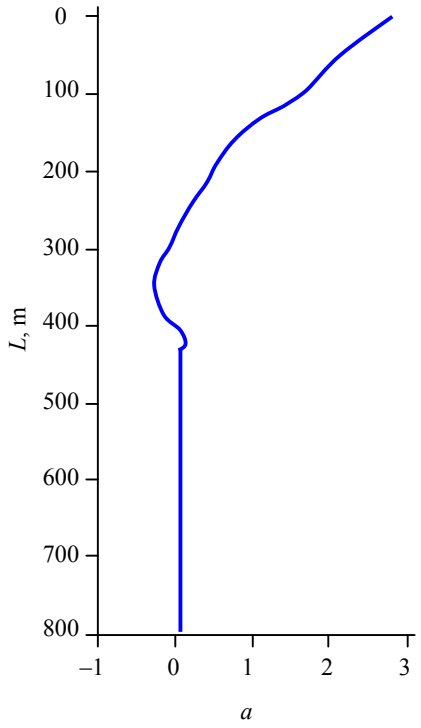


Fig. 3. Distribution of the parameter of internal stability, a with depth L for a typical well of the Pauzhet field

By way of an example consider the distribution of internal stability with depth for a typical well of the Pauzhet flash-steam field with its typical feeding conditions, that is the conditions of well operation correspond to point 2 in Fig. 1. The distribution of the parameter of internal stability with well depth as calculated according to the WELL-4 model is presented in Fig. 3. Boiling starts in the well at the depth of 434 m. The plot shows that within the scope of depths from 280 to 400 m the parameter is negative, $a < 0$, that is the flow features an internal instability.

To maintain flow stability within a given element of the well that stays within the indicated interval, a respective reaction should occur of the external pressure on that element. Moreover, such a reaction delay should be shorter than the typical time of instability development. If, on the other hand, the considered element is surrounded by other elements, as unstable as the first one, the internal instability will find a possibility to develop. Therefore there is always a range within the well in which the local conditions are present for the development of flow instability. In the best possible case such instability will look as some oscillation of

parameters at wellhead that does not preclude the operation of the well. These oscillations that are believed to be a natural property of a flash-steam well, are important for instability development. The considered type of instability develops from the wellhead to the well foot. If there are no conditions for instability development at the wellhead, it will not manifest itself even if the well as a whole disagrees with the condition (3). Parameter oscillations help in the formation of the needed conditions at the wellhead. In case condition (3) is satisfied for the flash-steam geothermal well as a whole, such oscillations will not develop into a general flow instability.

Conclusion. The main conclusion from this study is the statement that generally the condition for stable flow in a flash-steam geothermal well (to the exclusion of its local stretches) should be the positive value of the derivative of the internal well foot pressure, defined as the sum of the wellhead and the internal pressure drop over the discharge, see condition (3).

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