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Methods of Support for the Steam-Water Well Operation in Self-Discharge Mode

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ABSTRACT

The conditions for the stable operation of a steam-water geothermal well are considered based on an analysis of the characteristics reflecting the relationship of bottomhole pressure and the flow rate for the well and the aquifer. These conditions ensure the well operation in a self-discharge mode when the static water level is below the wellhead. The main ways and a brief overview of methods for ensuring the operation of steam-water wells in the self-discharge mode are presented. The factors that contribute to the occurrence of instability are specified, and recommendations are given for ensuring the operation of the steam-water well in the self-discharge mode.

1. INTRODUCTION

Geothermal energy is a promising area for solving world's energy problems and developing actively (Bertani 2016; Lund and Boyd 2016). Scale of development of geothermal resources has already exceeded the scope of subsidized projects, and increasingly carried out on commercial basis. Moreover, in Kamchatka (Russia), geothermal energy competes with traditional energy sources that are subsidized (Kolesnikov et al. 2015).

In geothermal projects, increased attention is paid to the efficient use of resources, including the rational use of wells collections, as their construction takes up large part of associated costs. In recent years, much attention is paid to the stimulation of wells, which allows to increase their efficiency (Grubelich et al. 2015; On and Andrino 2015; Pasikki et al. 2010; Siratovich et el. 2015; etc.). The possibility of energy production without elevation of geothermal fluids to the surface has been investigated (Alimonti et al. 2016; Holmberg et al. 2016; Wołoszyn and Gołas 2016; Lous et al. 2015; etc.). This allows the exploitation of non-productive wells. More detailed processes also studied, that do not have obvious practical application, but have cognitive interest and possible practical application in the future (Pashkevich and Muratov 2015; Muratov and Pashkevich 2015).

Some geothermal wells do not naturally self-discharge the aquifer fluid and thus called non-self-discharge wells. Non-self-discharge wells are common in water-dominated geothermal fields, and can be found in many countries (Mubarok and Zarrouk 2017). Mubarok and Zarrouk notes that prediction of well to self-discharge is a key issue. However, any such prediction does not exclude the need for testing, including attempts to induce the self-discharge. Therefore, it is important to find reasons of inability for self-discharge operation of the well, and develop methods to eliminate them. This work devoted to these important questions.

2. THEORETICAL BASIS

2.1 Graphical representation of self-discharge conditions

Operating mode of the well depends on the characteristics of aquifer, reservoir opening, hydraulic characteristics of wellbore and conditions on the wellhead. It is convenient to illustrate the nature of operating regime of the well, including possibility of self-discharge operation, based on analysis of characteristics of the well and aquifer (feed zones), that reflect dependence of bottomhole pressure on flow rate. The characteristic of a typical well of the Mutnovka geothermal field in Kamchatka is shown in Fig. 1, Curve 1: depth to aquifer is 1400 m; the inner diameter to the depth of 1100 m is 0.225 m, deeper is 0.152 m; the fluid enthalpy is 1200 kJ/kg. The well feeds the steam-water mixture into a group separator with a constant wellhead pressure of 7 bar. The calculation of bottomhole pressure was performed using the mathematical model WELL-4 (Shulyupin and Chermoshentseva 2013). Some characteristics of the aquifer are marked 2, 3 and 4. The operation point is determined by the equality of bottomhole pressures in the well and aquifer, i.e. point of intersection of characteristics.

Aquifer characteristics represented with straight lines. This corresponds to steady-state feed conditions with linear law of filtration. The position of the starting point (at zero flow rate) is determined by the value of static pressure in reservoir. The slope angle of the characteristics is determined by filtration properties of geothermal reservoir and conditions of reservoir opening of a particular well. In fact, filtration in the aquifer, especially in bottomhole zone, may differ from the linear. In operation process, as a rule, the reservoir pressure drops and aquifer permeability reduces due to scaling in conducting channels. The scaling is particularly intense with the boiling zone expansion into the aquifer. Nevertheless, at some point in time, the filtration conditions in aquifer can be, almost always, considered as steady (or quasi-stationary), and linear dependence, in case of absence of more precise determination, can be considered as the first approximation for aquifer characteristics.

Operation points are absent for the aquifer characteristic 4, therefore the well cannot function on self-discharge. Excluding hypothetical options, the aquifer characteristics have a negative slope. Considering the kind of the well characteristic, at intersection point there are three variants of slopes: a positive slope of the well characteristic (Point B, Fig. 1); a negative slope of the well characteristic, which exceeds the slope of the aquifer characteristic (Point A); a negative slope of the well characteristic, which is smaller than the slope of the aquifer characteristic (Point C). For these points, the possibility of well operation requires a more detailed analysis of the flow stability.

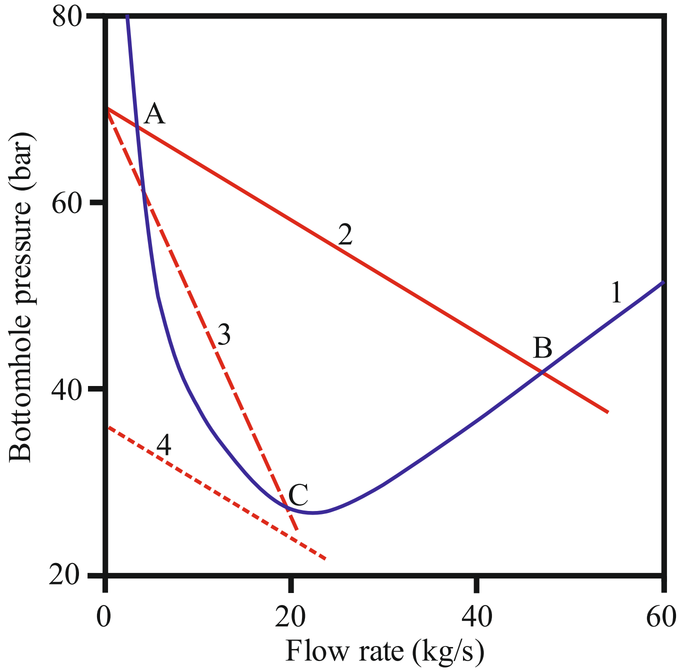


Figure 1: Characteristic of typical well of the Mutnovka geothermal field (Kamchatka) (1) and possible aquifer characteristics (2, 3 and 4).

2.2 Stability condition

Stable regime of well operation can be considered the regime under which there is no phases of unstable processes. In case of geothermal wells, such processes are due to flow instability. The flow instability, on the other hand, is due to the presence of conditions that contribute to development of nonstationarity at small perturbations of the flow parameters. In general form, the condition of stability in steam-water well is determined with correlation (Shulyupin 2017)

$$\frac{\partial \Delta p_i}{\partial G} + \frac{\partial p_w}{\partial G} > \frac{\partial p_z}{\partial G}, \tag{1}$$

where Δp_i is internal pressure drop (or sum of pressure drops by frictional, convective acceleration and gravity), G is mass flow rate, p_w is external wellhead pressure determining by down-stream conditions from wellhead, p_z is external bottomhole pressure (or pressure in level of upper boundary of feed zones for thick aquifer) determining by flow conditions in feed aquifer.

Correlation (1) coincides with the known Ledinegg condition (Ledinegg 1938; Nayak and Vijayan 2008; Ruspini et al. 2014). Usually, the Ledinegg's instability relates to static instability class (Boure et al. 1973; Ruspini et al. 2014). The correlation (1) is obtained based on analysis of dynamic processes, therefore, in such general form, it is only relevant in case of sufficiently rapid reaction of external pressures (p_w и p_z), but this is not always available. It should be noted that in our case there is a significant difference in factors that cause instability. The classical Ledinegg's instability is associated with the features of friction and phase transition caused by the heat flux at the channel wall. In our case, neither friction nor heat flux on the wall are not determining factors. In a two-phase flow, with an increase in flow rate, phase mixing intensifies, which reduces the ratio of average velocities of phases. Mixture density and gravity influence are reduced, internal pressure drop is reduced. Role of friction and acceleration is increased with increasing flow rate. Consequently, the violation of condition (1) can manifest with small influence of friction and acceleration. For manifestation of instability, in this case, the determining factor is gravitational force, and the amplifying factor is the phase transition during decompression, which further reduces mixture density. This case can be classified as gravitational instability. The coincidence of (1) with the Ledinegg's condition is a consequence of generality of the mechanism of instability development in both cases.

An important feature of the case under consideration is the possibility of instability development exclusively from wellhead to bottomhole (Shulyupin 2017). Bottomhole pressure response (right hand side (1)) in most cases is not able to influence the development of instability due to time delay, because instability development must reach of bottomhole. In the form (1), the stability condition can be used only for non-deep wells, or in the presence of factors that impede the development of instability at the wellhead, for example, the presence of throttling elements near the wellhead. In practice, the stability condition is advisable to use in the form

$$\frac{\partial \Delta p_i}{\partial G} + \frac{\partial p_w}{\partial G} > 0, \tag{2}$$

If the characteristic of the well is determined taking into account the dependence of the wellhead pressure on the flow conditions downstream of the wellhead, the angle slope of the well characteristic will characterize the left side of the relationships (1) and (2). According to condition (2), the flow can be stable only when the aquifer characteristic 2 when flow rate corresponds to point B (Fig. 1). In all other cases, the flow will be unstable, i.e. the well at a given constant wellhead pressure cannot operate stable on self-discharge.

Let us consider the Point C separately. As shown in (Droznin 1980), this variant of the combination of slopes is characteristic for the geyser regime. In this regime it is necessary that the aquifer pressure at zero flow rate (static bottomhole pressure) exceeds the hydrostatic pressure of the water column in the borehole. In referenced work, a laboratory setup has been described that successfully demonstrated an artificial geyser. We note that relationship (1) admits the possibility of operation with such a combination of characteristics, but, as noted, only under additional conditions. In some wells of the Pauzhetka geothermal field (Kamchatka), which have a low flow corresponding to the position of the operation point on the downward branch of the well characteristic, and have a small depth of the feeding zones, a pulsating operating regime was observed, i.e. the wells was operated at self-discharge, but the operation regime did not allow them to be used in practice.

The need of instability development from wellhead to bottomhole allows the well to operate at Point C, even when the static water level is below the wellhead, if there are no conditions for development of instability in the upper part of the well. Consider internal instability applying the condition (1) for the local well element (Shulyupin 2017): if in some local element the derivative of internal pressure drop is less than zero and this condition is fulfilled for conjugated elements, the reaction of external pressures to this element will be slowed down. This will create conditions for the onset of local instability. On the other hand, if the derivative of the internal pressure drop is greater than zero, the internal behavior of the element will stabilize the flow.

Internal stability is characterized by parameter (Shulyupin 2017)

$$a = \frac{G}{\left(\partial p / \partial z\right)} \frac{\partial}{\partial G}\left(\frac{\partial p}{\partial z}\right), \tag{3}$$

where a is a dimensionless parameter of internal stability.

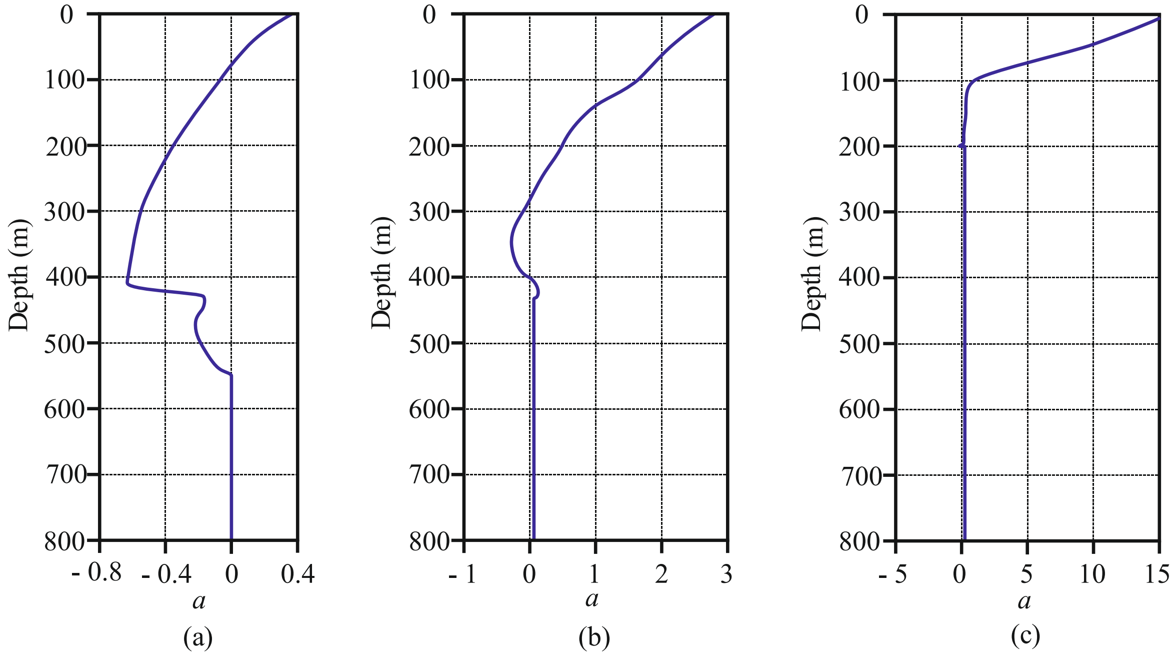
The positive value of this parameter indicates the presence of internal stability. This parameter can be interpreted as an exponent in the simplest dependence of pressure gradient on the flow rate.

$$\frac{\partial p}{\partial z} = kG^{a}, \tag{4}$$

where k is a coefficient.

It is easy to see that the right-hand side of (3), with considering (4), gives the required parameter.

Fig. 2 shows graphs of distribution of parameter a in depth, calculated using formula (3) and WELL-4 model. The parameters of the well correspond to average values for the Pauzhetka geothermal field (Kamchatka): wellhead pressure is 3 bar, depth to aquifer is 800 m, inner diameter is 0.2 m, enthalpy is 800 kJ/kg. The value of the left part (2), which characterizes stability of the flow in the well, for presented variations (a, b, c), is respectively: – 133, 88 and 65 kPa*s/kg.



Figuere 2: Change of the internal stability parameter with depth at varies flow rate: (a) – 10 kg/s; (b) – 29 kg/s; (c) – 60 kg/s.

In area of single-phase flow, the values of stability parameter are practically constant and close to zero (the pressure gradient is mainly determined by the hydrostatic pressure of water). In two-phase flow area, the parameter undergoes significant changes. The WELL-4 model assumes several regimes of two-phase flow, which reflected in the charts for small (a) and average (b) flow rate. As the flow rate increases, the area of internal instability reduces. At a flow rate of 60 kg/s (c), this area is limited to two meters near the level of evaporation start. At a flow rate of 65 kg/s, this area completely absent, and at a flow rate of 5 kg/s this area extends to entire length of the well. With an average flow rate of 29 kg/s (b) for the field, the flow in the upper part has an internal stability. Note that in work (Shulyupin 2017), the calculation of this variant is given, but it improperly indicates to another flow rate. At a flow rate of 10 kg/s (a), despite the non-compliance of stability condition for the well, there is an area with internal stability in the upper part.

The presence of internally stable flow area in the upper well part can contribute to appearance of metastable flow. In this case, condition (2) is not satisfied, but there is no necessity in development of instability from the wellhead to bottomhole. However, the presence of area with internal instability in the lower part contributes to clustering of the flow structure. Clustering causes significant fluctuations in flow and pressure, which contribute to emergence of conditions for development of instability in the upper part of the well. Thus, we cannot confidently assume instability in the case when the operation point is on the descending branch of the well characteristic in the immediate vicinity of extremum point.

2.3 Basic ways for self-discharge support

To ensure well operates in self-discharge, the operating point (the point of intersection of the characteristics of aquifer and well) should be on the upward branch of the well characteristic (Fig. 1). There are two main reasons why well cannot operate in self-discharge: an inadequate aquifer and well characteristics.

If the static water level is below the wellhead, the steam-lift provides operation of the wells. Boiling reduces the density of the fluid in the well, ensuring its rise to the surface. Unsuccessful stimulation of the steam-lift can also be the reason for the lack of well operation on self-discharge.

Thus, it is necessary for the operation point to be at required location to support self-discharge operation of steam-water well. If the operation point is initially located on the descending branch, or there is no intersection of the characteristics, the required result can be achieved in two ways. The first way is change in the aquifer characteristic; the second is change in the well characteristic. Recall, the well characteristic should be considered taking into account the dependence of the wellhead pressure on the conditions of downstream flow from the wellhead.

Another way to support well self-discharge operation is the choice of steam-lift stimulation technology, in case when characteristics of the well and aquifer correspond to this mode.

3. SOME METHODS TO ENSURE OF STEAM-WATER WELL OPERATION IN SELF-DISCHARGE MODE

3.1 Change in aquifer characteristic

Analysis of Fig. 1 shows that the high location of the initial point of the aquifer characteristics increases the chances for achieving a steady flow in the self-discharge regime (see aquifer characteristics 4 and 2). Accordingly, self-discharge support is possible with increasing initial aquifer pressure. This can be achieved with reinjection of used heat agent and unused separated water into the aquifer. It is also possible to reduce the production volume in the wells that interact with the one under consideration. These methods require coordination with general strategy of field development, thus their thorough review in this paper is not necessary.

Another way to support a steady flow in the self-discharge mode is lowering the slope of the aquifer characteristics, i. e. improving aquifer permeability (Fig. 1, characteristics of the aquifer 2 and 3). As noted beforehand, active research in well stimulation is underway, and it can be divided in two areas: aquifer stimulation and steam-lift stimulation. In this section, aquifer stimulation is considered.

There are many methods to stimulate the aquifer. Analysis of these methods can be a topic of separate discussion. In present article, experience of Russian specialists is discussed. In the Mutnovka field (Kamchatka) exploitation, good result showed simplest method: multiple stimulation with fast decompression (Shulyupin and Chernev 2015). The key difference between this method and methods alike is rapid opening of the wellhead under pressure and multiple repeated operations. To open the wellhead, special devices are used; giving time of full opening of about 0.1 s. Rapid opening allows creation of maximum dynamic and thermal loads in the aquifer bottomhole zone. This promotes the removal of scaling in permeable channels and the formation of new channels.

Widespread cause of stability loss and self-discharge loss of steam-water wells in Kamchatka is a decrease in aquifer conductivity (permeability) due to scaling in the bottomhole zone of the aquifer. Experience shows that steam-lift stimulation with transfer to free discharge allows partial removal of scaling. It for a while returns required self-discharge mode at required exploitation wellhead pressure. This is the simplest, but not the most effective way. The aquifer stimulation method of multiple excitations with fast decompression at the wellhead appears to be more effective.

3.2 Change of well characteristic

3.2.1 Change of exploitation pressure

Well operation in self-discharge mode can also be done with change in well characteristic. The simplest way to change the well characteristic is the change of exploitation pressure. Fig. 3 shows two calculated characteristics of the well. First characteristic is similar to the characteristic in Fig. 1 (for wellhead pressure of 7 bar). The second characteristic corresponds to the same well but at

6 bar. When the aquifer characteristic is 3, reduction in wellhead pressure transforms the well from an unstable state (point A) to stable (point B). However, this method is not always justified, since the reduction in exploitation pressure in one well requires the relevant reduction in other wells operating for the same power plant, which leads to decrease in the efficiency of operation.

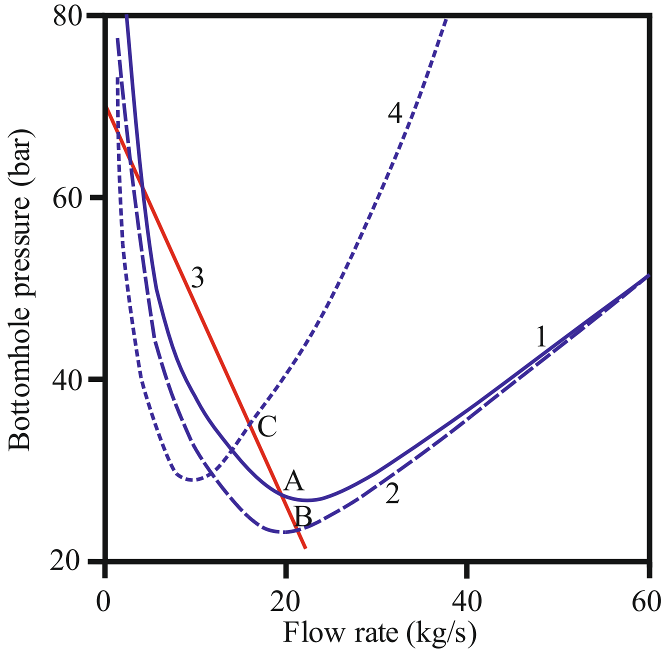


Figure 3: Characteristics of the well and aquifer: 1 – well with wellhead pressure of 7 bar, 2 – well with wellhead pressure of 6 bar, 3 – aquifer, 4 – well with reduced diameter.

3.2.2 Change in conditions of heat agent transportation from the well

Another way is the change of coolant transportation conditions from wellhead to power plant. These changes relate to the second term from the left side of (2). It is necessary to seek the maximum value of this term with given pressures at the power plant and wellhead entrance. As an example, consider the case where the fluid from the well is transported to the group separator of the power plant through the steam-water mixture pipeline, and the pipeline has an unjustifiably large diameter and ascending sections. Such cases occurred at the Mutnovka field (pipelines from wells A-2, A-3, 4-E). In such pipelines, the pressure drops due to friction are minimal, but the ascending sections give noticeable gravitational pressure drop values, which decrease with increasing flow rate. Thus, with a presence of noticeable overall pressure drop from the wellhead to the separator, the corresponding term (2) can have a negative value, which negatively affects the stability. Reduction of pipeline diameter can increase the stability of the well operating regime, without significant change of overall pressure drop during transportation.

Taking into consideration the importance of downstream conditions of the wellhead, defined by the second term of the left side of (2), it is worth paying attention to one important practical aspect. Stable operation of the well at a given wellhead pressure during the test does not guarantee this well operation at the same wellhead pressure. Sometimes this is due to the time factor, since the well characteristics vary from the time of the test to operation attempt. But in some cases, the time factor is not relevant. For example, attempts to put into operation the wells A-2 and A-3 at the Mutnovsky field were made just before and after the tests. These wells showed stable operation during the test at the wellhead pressure ranges of 7.0-11.9 bar and 3.0-12.2 bar, respectively, but were incapable of stable operation with wellhead pressure of 7.0-7.5 bar.

The fact is that the test conditions differ substantially from the operating conditions in the second term of the left side of (2). In operation, these wells should work for a group separator, which maintains relatively constant pressure independent of well flow rate, which ensures a relative stability of wellhead pressure, i.e. the second term on the left side of (2) to zero, and with unreasonably high pipeline diameter and with presence of ascending sections can even take negative values. The test is carried out at various wellhead pressure levels, which are provided by throttling the flow on the valve located in front of the inlet to the flow meter. That is, near the wellhead there is a significant drop, which significantly depends on the flow rate, and gives the necessary step of wellhead pressure. In this case, the value of the second term on the left side of (2) is significant and positive, which increases the stability. This explains the fact of increased stability of the well operation during test.

3.2.3 Flow throttling at the wellhead

As shown in (Shulyupin and Chernev 2015), positive changes in well characteristic can be achieved with simple flow throttling at the wellhead. Fig. 4 shows the characteristics of the averaged well of the Pauzhetka field, which operates on release into atmosphere through the throttle valve. The characteristics correspond to the local resistance of the valve 0, 5, 10, 20, 40 and 100. The extremum points are marked with crosses. Increase of throttling degree shifts the extremum point to the area of lower flow rate. In the case of the weak aquifer permeability (characteristic 1), this facilitates the transition to stable operation.

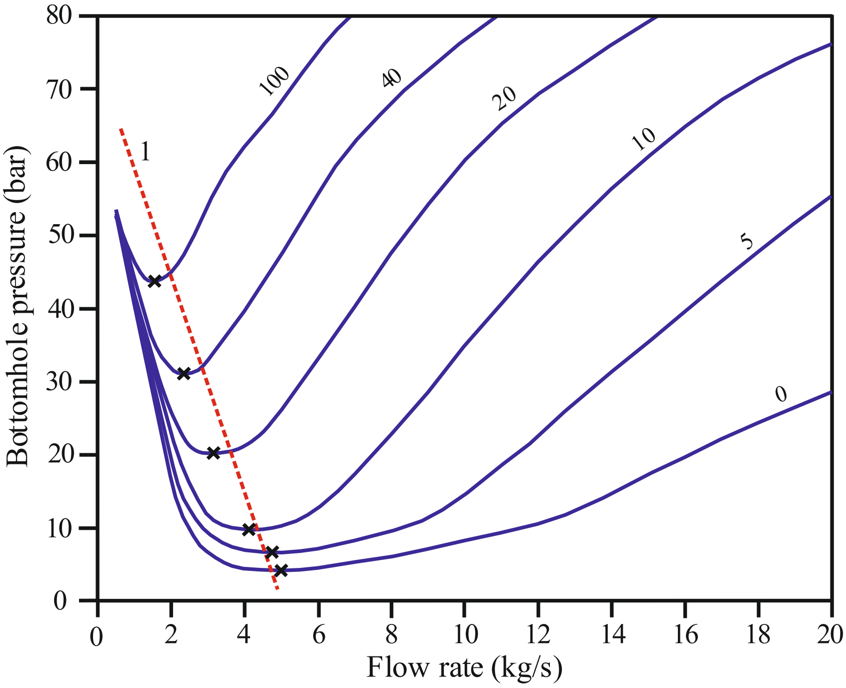


Figure 4: Characteristics of well with additional resistance coefficients of 0, 5, 10, 20, 40, 100. 1 is characteristic of feed zones.

In this way, at the Mutnovka field, wells 4-E and A-3 were put into operation, which could not work directly into the main pipelines. The required throttling degree was selected experimentally. The throttling valve acted as an element preventing the development of instability at the wellhead. Considering the possibility of metastable flow, in this case the experimentally selected regime corresponds to the metastable flow. Indeed, the parameters of these wells do not meet the condition (2). The flow-rate parameters and the results of calculating the terms on the left side of (2) under the WELL-4 program presented in Table 1. In both cases, the sum of the terms on the left side of (2) is less than zero. With the specified criteria, according to calculations, both wells should not work stably. Nevertheless, in practice there is a stable flow. Metastable flow has not yet been studied. It can be assumed that such a flow is not a reliable ally of stability. Note that the 4-E well before decommissioning was able to operate several years, and the A-3 well quickly went out of operation.

Table 1: Initial data and terms of condition (2) for wells 4-E and A-3 of the Mutnovka geothermal field

Parameter	Well 4-E	Well A-3
Welhead pressure (bar)	8.0	9.2
Mass flow rate (kg/s)	20.9	18.1
Enthalpy (kJ/kg)	1110	1261
Pressure in separator (bar)	6.3	6.3
$\partial\Delta p_i / \partial G$, (kPa*c/kg)	– 116	– 74
$\partial\Delta p_w / \partial G$, (kPa*c/kg)	16	32

3.2.4 Change of well casing

Good result for support of stability can give a change of well characteristic by pipe installation within the existing well casing, which reduces the internal diameter of the channel. Fig. 3, item 4, the well characteristic calculated under the same conditions as characteristic 1, apart from the diameter of the upper part (changed from 0.225 m to 0.154 m). As can be seen in the figure, the working point for these characteristics (Point C) is in the region of steady flow.

This method was implemented at the well A-2 of the Mutnovka geothermal field. For a long time, the well was operated under periodic self-stopping. The change in the operating mode was accompanied by temperature loads on the casing, leading, ultimately, to its rupture. Insert installation was originally conceived as an action to eliminate the consequences of the casing rupture of the well. After the reconstruction, the well began to work stably, without self-stopping. A similar measure, but with the main goal of ensuring stability, was implemented at the Geo-2 well of the Mutnovka field and also had a positive result.

Mubarok and Zarrouk (2017) noted that the reduced diameter is one of the reasons for not to be able to operate on self-discharge. Theoretically, it can be assumed that there is a case where the stability state can be achieved by increasing the diameter. For example, with aquifer characteristic that passes below the extremum point of curve 4 and above the extremum point of curve 1 in Fig. 3. But such a case should be regarded only as hypothetical. In practice, it is the bigger diameter that can be a factor of instability, including preventing work on self-discharge.

3.2.5 Elimination of defects

Instability may be due to defects made in the course of well construction. For technical reasons the construction project is not always fully implemented. Defects can also occur during the operation and idle of the well. An example is noted breach of the casing of the well A-2. Defects are often in the operating and, especially, in the idle wells. For example, salts are deposited in the places of the most intensive change in the thermodynamic parameters. Elimination of these and similar defects contributes to the operation of the well on self-discharge.

3.2.6 Steam-lift stimulation

If the static water level is below the wellhead, some procedures must be performed to start the steam-lift for the well which must operate in the self-discharge mode. Such procedures can be called "steam-lift stimulation". The main element of these procedures is the removal of the relatively cold water column from the well. The unsuccessful choice of the way to stimulate the steam-lift and the technology of its implementation can lead to failure to attempt ensure self-discharge. It should be noted that self-heating of a well with a closed wellhead valve can also be considered as an element of the steam-lift stimulation.

Mubarok and Zarrouk (2017) describe several methods in detail, which can be attributed to steam-lift stimulation. This list can be supplemented with ways that were actively used in the development of the Pauzhetka geothermal field. In the early stages, the steam-lift stimulation was carried out in a simple way – carbide was poured into the well. Upon contact with water, carbide produced gas, gas-lift facilitated the fluid in the well, the facilitated fluid was removed from the shaft under the bottomhole pressure and further activated steam-lift. In some wells the swabbing was used to remove the cold-water column.

Consider one of the cases that indicate the importance of choosing the method of steam-lift stimulation, where the well has two feeding zones. The upper zone contains relatively cold water; the lower zone contains relatively hot water. In a static state with an open upper wellhead valve there is no interchange between the zones (Fig. 5a).

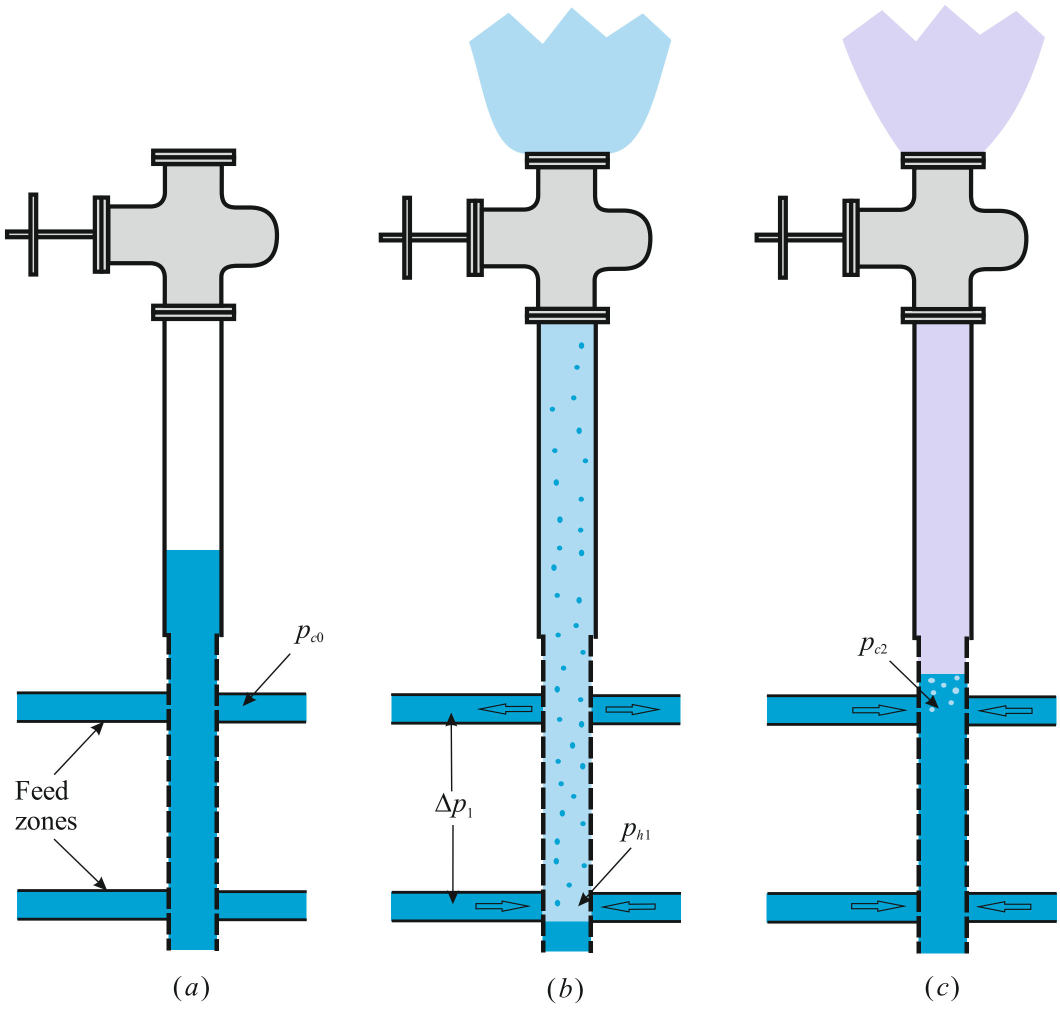


Figure 5: Inflow of fluid to the well: (*a*) – static state with an open wellhead latch; (*b*) – stable operation in the steam-lift mode; (*c*) – state after rapid opening of the wellhead with stimulation by air injection.

For stationary operation in the steam-lift mode, the boiling level drops to the lower zone (Fig. 5b). In the static state, between the zones in the well there is water, and when working in the steam-lift mode – a steam-water mixture. The upper zone does not supply cold water to the well due to decrease in the pressure difference between the zones, with the condition

$$p_{c0} < p_{h1} - \Delta p_1 , \quad (5)$$

where p_{c0} is pressure in the upper zone in the static state, p_{h1} and Δp_1 – pressure in the well at the level of the lower zone and pressure difference in the well between the zones when operating in the steam-lift mode.

In this case, in the steam-lift mode, the enthalpy of fluid is determined exclusively by the lower hot zone.

If the steam-lift in this well is stimulated with air injection method (air compression discharge stimulation (Mubarok and Zarrouk 2017)) with a fast opening of the wellhead, in the initial stage of depression in the upper zone the pressure p_{c2} (Fig. 5b) will be below p_{c0}, therefore a relatively cold fluid will enter the well. The presence of a cold fluid will reduce the efficiency of the steam-lift in the initial stage, and the well may not enter the stationary operation mode.

It is advisable to stimulate such a well by removing the cold-water column with a swab. Speed of wellhead valve opening can also be considered. It should be noted that in the Pauzhetka geothermal field in similar cases, when the air injection method was ineffective, a successful result was achieved with swabbing method.

4. RECOMMENDATIONS FOR ENSURING THE SELF-DISCHARGE MODE OF OPERATION

The considered methods can be classified by three ways and six groups (Fig. 6). It is also possible to identify the main factors that can obstruction in the operation of the well in a self-discharge mode, when the well opens the reservoir with the known enthalpy of the fluid and operates at predetermined conditions at the wellhead: low initial reservoir pressure (at zero flow rate); low conductivity of the aquifer; adverse downstream flow conditions from the wellhead; inadequate (high) casing diameter; technical defects in the construction of a well, or defects occurring during its operation or idle time; unsuccessfully chosen method and technology of the steam-lift stimulation.

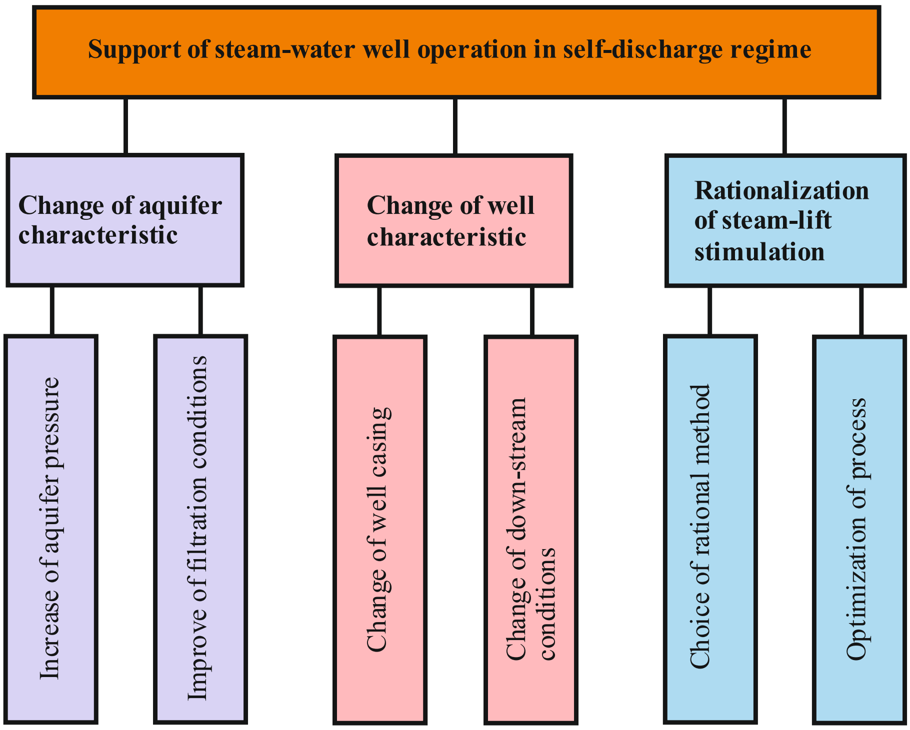


Figure 6: Ways for ensuring stable operation of steam-water wells.

In practice, when encountering the difficulties of ensuring the well operation in the self-discharge mode, it is first of all necessary to find the reasons for their occurrence, and then choose the way and the group in which to search for the ways to eliminate the identified causes. As a rule, there is no firm confidence in the reasons for failure to ensure the well operation in self-discharge mode. There are only some assumptions. In such cases, it is reasonable to solve the problem by selecting methods considering the level of costs and possible irreversible consequences of their implementation. For example, assuming the low conductivity of the aquifer, first it is reasonable try to solve the problem by stimulating the feed zones, and only as an extreme measure, decreasing the internal diameter of the well. Installing the inside pipe to reduce wellbore diameter is a difficult and costly task. After the inside pipe installation, the well may lose its potential, which could be preserved with other methods. It should be noted that the most productive well of the Mutnovka geothermal field (Well 042) was previously considered unproductive, but went into self-discharge mode with the aquifer stimulation. If a pipe were installed inside it, perhaps stimulation would not give a positive result, and if the result was positive, the productivity would definitely be much less.

5. CONCLUSION

Based on analysis of the hydrodynamic stability conditions and consideration of various aquifer characteristics, three ways have been identified and six groups of methods for ensuring the stable operation of steam-water wells (Fig. 6). Faced with difficulties in the well operation in self-discharge mode, it is necessary to find the causes of their occurrence, and, taking this into account, choose the most suitable methods. At the same time, it is necessary to give preference to the simplest in implementation methods that do not interfere with further attempts to provide the necessary mode of operation.

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