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Methods for ensuring of stable operate of steam-water wells

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Abstract. The conditions for the stable operation of the steam-water geothermal well are considered on the basis of the analysis of the characteristics reflecting the dependence of the bottomhole pressure on the flow rate for the well and the feed aquifer. When the position of the static water level is below the wellhead, these conditions determine the principle possibility of the steam-lift production of the fluid in the self-discharge regime. When constructing the characteristics of the well, it is necessary to take into account the dependence of the external wellhead pressure, determined by the flow downstream from the wellhead, on the flow. A sufficient condition for stable steam-lift operation is the finding of a working point (the intersection of characteristics) on the ascending branch of the characteristic of the well. In the presence of factors that inhibit the development of instability at the wellhead, the possibility of steam-lift operation while finding a working point and on the descending branch near the extremum of the well characteristic is not ruled out.

Some methods of changing the characteristics of a well and an aquifer that contribute to the achievement of the required location of the working point are considered. The importance of choosing the method of excitation of a well and the technology of its implementation in the presence of the required location are noted. The reasons for appearance of difficulties of the steam-lift operation of the well are indicated. It is recommended, having faced in practice with such difficulties and having found the reasons for their occurrence, choose the most appropriate ways of eliminating them, preferring the simplest in the implementation the methods that, in case of failure, will not interfere with further attempts to provide the necessary mode of operation.

Keywords: steam-water well, steam-lift, self-discharge, feed aquifer, static water level

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Introduction

Currently, geothermal resources are actively used both for the conversion of thermal energy into electrical energy (Bertani, 2016), and in the area of direct use of fluids (Lund, 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 new conditions the increased attention is paid to problems of rational use of constructed wells, as their construction takes up large part of associated costs of geothermal projects. In recent years, much attention is paid to the stimulation of wells, which allows to increase their efficiency (Grubelich et al., 2015; On, 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, Gołas, 2016; Lous et al., 2015; etc.). This allows the exploitation of non-productive wells. Thermophysics processes in wells are investigated and other ways to increase their productivity are being developed (Alishaev, Azizov, 2011; Alkhasov et al., 2016; Shulyupin, Chernev, 2015; Shulyupin et al., 2017).

A significant proportion of the world's exploited geothermal resources is provided by the development of water-dominant high-temperature geothermal fields (steam-water fields). The number of such fields is greater than the number of single-phase steam fields. These fields have a higher energy potential compared to single-phase water fields. In the majority of wells in the steam-water fields, including all the wells of the largest fields in Russia, the level of reservoir water is below the wellhead. The operation of such wells is carried out at the expense of steam-lift. Steam-lift is a type of gas-lift, when the rise of the fluid is carried out by facilitating the fluid due to its boiling up. At the same time, the well operates in the self-discharge mode. The steam-lift works as natural gas-lift, since boiling is provided by the flow of hot water from the reservoir.

At the same time, there are a large number of wells in the steam-water fields that are unable to operate in self-discharge mode (Mubarok, Zarrouk, 2017). In addition, experience shows that productive wells lose their productivity over time and there comes a time when the steam-lift does not provide the necessary mode of operation. Therefore, it is important to identify the conditions that ensure the steam-lift operation, to establish the factors that reduce the efficiency of the steam-lift, and to develop methods to ensure the operation of the well in self-discharge mode. This is the subject of this paper.

Theoretical basis for determination of well operation mode

Operation mode of the well depends on the characteristics of aquifer, reservoir opening and hydraulic characteristics of wellbore and conditions on the wellhead. The determination of operation mode of wells is conveniently carried out on the basis of an analysis of characteristics of 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 the bottomhole pressure (hereinafter, the bottomhole pressure is referred as the pressure at level of upper boundary of aquifer) is made according to the mathematical model WELL-4 (Shulyupin, Chermoshentseva, 2013). For the characteristic of the aquifer capacity it is proposed to take the Dupuit formula (Droznin, 1980)

$$G = \frac{2\pi k M (p_a - p_z)}{\nu \ln(R/r)}, \tag{1}$$

where G is mass flow rate, k and M are permeation rate and thickness of aquifer, p_a and p_z are aquifer and bottomhole pressures, ν is kinematic viscosity, R is radius of funnel, r is radius of well.

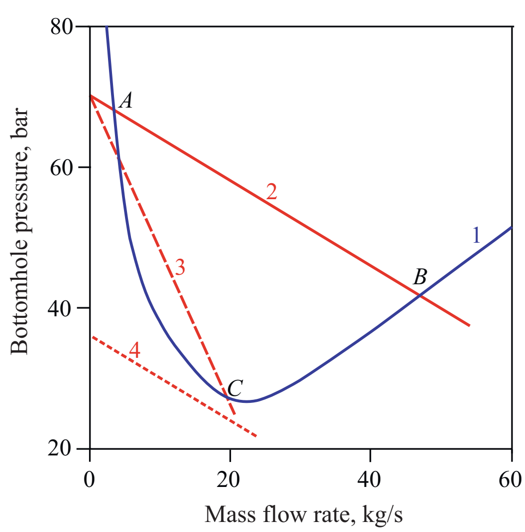

Fig. 1. Characteristic of typical well of the Mutnovka geothermal field (Kamchatka) (1) and possible aquifer characteristics (2, 3 and 4)

This formula can be converted to a linear dependence of the bottomhole pressure on the flow rate

$$p_z = p_a - bG, \tag{2}$$

where

$$b = \frac{\nu \ln(R/r)}{2\pi k M}. \tag{3}$$

Some aquifer characteristics represented with straight lines, according formula (2). Those characteristics 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 well and aquifer characteristics.

The straight lines for aquifer characteristics correspond 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, conditions of reservoir opening of a particular well and viscosity of fluid. 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.

Stable regime of well operation can be considered as the regime under which there are no phases of unstable processes. In case of geothermal wells, such processes are due to flow instability. The flow instability 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 relationship (Shulyupin, 2016)

$$\frac{\partial \Delta p_i}{\partial G} > \frac{\partial p_z}{\partial G} - \frac{\partial p_w}{\partial G}, \tag{4}$$

where Δp_i is internal pressure drop (or sum of pressure drops by frictional, convective acceleration and gravity), p_w is external wellhead pressure determining by downstream conditions from wellhead, in this relationship the bottomhole pressure p_z is external parameter determining by flow conditions in feed aquifer.

Relationship (4) coincides with the known Ledinegg condition (Ledinegg, 1938; Nayak, Vijayan 2008; Ruspini et al., 2014). Usually, the Ledinegg's instability relates to static instability class (Boure et al., 1973; Ruspini et al., 2014). In our case the relationship (4) is obtained based on analysis of dynamic processes, therefore, in such general form, it is only relevant in case of sufficiently rapid reactions of external pressures (p_w и p_z), determining by flows downstream from wellhead and upstream from bottomhole, on flow-rate changes. 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 (4) can manifest with small influence of friction and acceleration. For manifestation of instability, in this case, gravitational force is the determining factor, and the phase transition during decompression is the amplifying factor, which further reduces mixture density. This case can be classified as gravitational instability. The coincidence of (4) with the Ledinegg's condition is a consequence of generality of the mechanism of instability development in both cases.

An important feature of the gravitational instability is the possibility of development exclusively from wellhead to bottomhole (Shulyupin, 2016). Bottomhole pressure response 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 (4), the stability condition can be used only for non-deep wells. In practice, the stability condition is advisable to use in the form

$$\frac{\partial \Delta p_i}{\partial G} + \frac{\partial p_w}{\partial G} > 0. \tag{5}$$

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 relationship (5). According to the condition, the flow can be stable only at 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 steam-lift is unable to ensure stable well operation at a given constant wellhead pressure.

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 (4) 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 operation mode was observed, i.e. the wells was operated at self-discharge, but the operation mode did not allow them to be used in practice.

Consider the basic condition (4) for a certain element of the channel. If the left part, which characterizes the internal pressure drop, is greater than zero, the instability can only be ensured by the reaction of external pressures to a change in flow rate. Such a flow has internal stability; the element itself has a stabilizing effect. If in the element the derivative of the internal pressure drop is less than zero and this condition is fulfilled for the elements associated with it, the reaction of external pressures on this element will be slowed down, which will create conditions for the onset of instability. Applying condition (4) for the local element of the well in (Shulyupin, 2016) the parameter is introduced

$$a = \frac{G}{(\partial p / \partial z)} \frac{\partial}{\partial G}\left(\frac{\partial p}{\partial z}\right), \tag{6}$$

where a is a parameter of internal stability, $\partial p/\partial z$ is pressure gradient.

The calculation of the distribution of the parameter a in depth showed (Shulyupin et al., 2018) that with high flow rates throughout the well, the condition of internal stability can be satisfied. With a decrease in flow rate, an area of internal instability forms in the lower part of the steam-water column, expanding as flow rate decreases. At low flow rates, the region of internal instability covers all the steam-water flow. It is important to note that if the condition (5) is violated in the upper part of the well a sufficiently large area of internally stable flow can exist, serving as a barrier to the development of instability from the wellhead to the bottomhole.

In this connection, condition (5) should not be considered as absolute, in violation of which the flow must necessarily be unstable. The transition from stable to unstable operation mode will be determined by the scale of the instability that is formed in the area of internal instability and the stabilizing ability of the area of internal stability. When the flow rate decreases, for example, in the case of salt deposits in the bottomhole zone, the area of internal stability will decrease, and a moment will come when fluctuations in flow parameters coming from the area of internal instability will lead to instability at the wellhead and self-stop of well. At the same time, it is impossible to deny the possibility of the existence of a metastable flow, when condition (5) is not fulfilled, but there is no necessary development of instability from the wellhead to bottomhole. However, guaranteed well operation in steam-lift mode is ensured by fulfilling condition (5), corresponding to finding the operation point on the upstream branch of the well characteristic.

If the operation point is initially located on the descending branch, or there is no intersection of the characteristics at all, the necessary location of the operation point can be achieved in two directions. The first is the change in aquifer characteristic. The second is the change in well characteristic. Note that the well characteristic should be considered taking into account the dependence of the wellhead pressure on the flow conditions downstream from the wellhead. Another direction in the provision of steam-lift operation, in case of the necessary combination of well and aquifer characteristics, is the choice of the method and technology for initiating a well. Because of the existing diversity, not all methods and technologies can initiate the exit to operation parameters.

Some methods to ensure steam-lift operation

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 (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. The second area in domestic practice is called “well excitation”.

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, the simplest method showed good result – multiple stimulation with fast decompression (Shulyupin, 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 spontaneous termination of steam-lift (term “self-stop” is used) in Kamchatka is decrease in the aquifer conductivity due to scaling in its bottomhole zone. 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 returns required self-discharge mode at required exploitation wellhead pressure for a while. 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.

The simplest method to change the well characteristic is the change of exploitation pressure. Fig. 2 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

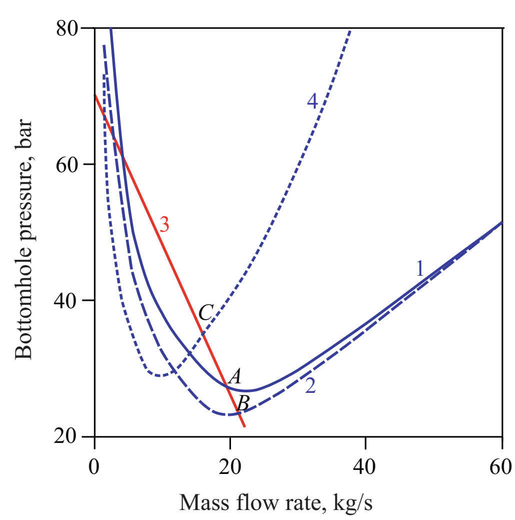

Fig. 2. Characteristics of the well and aquifer: 1 – well with wellhead pressure of 7 bar, 2 – well with wellhead pressure of 6 bar, 3 – aquifer, 4 – well with reduced diameter

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.

Another method is the change of fluid transportation conditions from wellhead to power plant. These changes relate to the second term from the left side of (5). It is necessary to seek the maximum value of this term with given pressures at the power plant and wellhead entrance. As an example, let us 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 (5) can have a negative value, which negatively affects the stability. Reduction of pipeline diameter can increase the stability of the well operation mode, 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 (5), 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 (5). 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 (5) is close 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 (5) is significant and positive, which increases the stability. This explains the fact of increased stability of the well operation during test.

As shown in (Shulyupin, Chernev, 2015), positive changes in well characteristic can be achieved with simple flow throttling at the wellhead. The throttling shifts the extremum point to the area of lower flow rate. In the case of the weak aquifer permeability, this can transfer the operation point in ascending branch of the well characteristic.

In this method, 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. Considering the possibility of metastable flow, in this case the experimentally selected regime corresponds to the metastable flow. Indeed, the calculations according to the WELL-4 program showed that the parameters of operation of these wells do not correspond to condition (5). In both cases, sum of the terms on the left side was less than zero (Shulyupin et al., 2018), i.e. according to calculations, both wells should not operate 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.

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 (Shulyupin, Chernev, 2015). Fig. 2, item 4 shows 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 operation point for these characteristics (point *C*) is in the region of stable 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-stop. 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 operate stably, without self-stop. 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.

In the work (Mubarok, Zarrouk, 2017), it is 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. 2. 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.

Instability can 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 given for the breach of 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.

If the static water level is below the wellhead, for the well operation in the self-discharge mode, some procedures must be performed to start the steam-lift. Such procedures in international practice relate to the stimulation of wells, in domestic practice, as noted, a special term is used for them – "well excitation". The main element of these procedures is the removal of a column of relatively cold water from a well. Unsuccessful choice of the method of excitation and the technology of its implementation can lead to failure of the attempt to enter the well into the operation mode.

In the work (Mubarok, Zarrouk, 2017), several methods are described in detail, which can be attributed to steam-lift stimulation. Note that self-heating of a well with closed wellhead valve, which is actively used both in Russia and abroad, can also be considered as an element of the excitation procedure. This list can be supplemented with methods 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 method – 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.

Let us 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. 3*a*).

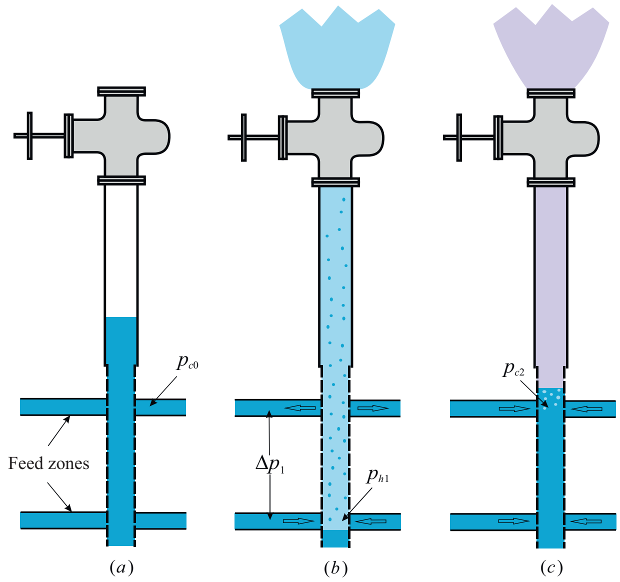

Fig. 3. Inflow of fluid to the well: (a) – static state with an open wellhead latch; (b) – stable operation in the steam-lift mode; (c) – state after rapid opening of the wellhead with stimulation by air injection

For stationary operation in the steam-lift mode, the boiling level drops to the lower zone (Fig. 3*b*). 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. In case of operation at condition $p_{c0} < p_{h1} - \Delta p_1$ (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) by reducing the pressure drop between zones, the upper zone does not deliver, but receives fluid. 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, Zarrouk, 2017)) with a fast opening of the wellhead, in the initial stage of depression in the upper zone the pressure p_{c2} (Fig. 3*c*) 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.

Recommendations for ensuring operation of wells in steam-lift mode

The considered methods can be classified by three ways: change of aquifer characteristic, change of well characteristic, rationalization of excitation process. In each way, two groups can be distinguished. The first way includes an increase in the static pressure of the reservoir (external aquifer pressure) and an improvement in filtration conditions. The second way includes a change in the well design (including the elimination of defects) and a change in the conditions for transporting fluid from the wellhead. The third way includes a choice of a rational method of well excitation and a choice of technology for its implementation. It is also possible to identify the main factors that can impede of steam-lift operation of well in self-discharge mode with predetermined conditions at the wellhead for well that has opened a reservoir with a known enthalpy of the fluid:

- 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.

In practice, when encountering the difficulties of ensuring the well operation in the steam-lift 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 the methods to eliminate of the reasons. As a rule, there is no firm confidence in the reasons for failure to ensure the well operation in steam-lift 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 domestic well (Well 042 in the Mutnovka geothermal field) 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.

Conclusion

The possibility of steam-lift operation of geothermal wells is determined by conditions of combination for well and aquifer characteristics, reflecting the dependence of bottomhole pressure on the flow rate. In this case, the well characteristic should be obtained taking into account the dependence of external wellhead pressure, determined by the flow downstream from the wellhead, on the flow rate. A sufficient condition is to find an operation point on ascending branch of the well characteristic. It does not exclude the possibility of operation when the operation point is found and on the descending branch near the extremum point of the characteristic. This possibility increases if there are additional factors hindering the development of instability at wellhead (for example, throttling at wellhead). These factors are formally expressed in the positive and significant value of the second term on the left side of condition (5).

Changing the characteristics of well and aquifer can achieve the desired combination. With the required combination, it is important in each particular case to correctly choose the method of well excitation and the technology for its implementation.

Having in practice the difficulties of steam-lift well operation, it is necessary to find the reasons for their occurrence. Having found out the reasons, it is necessary to choose the most appropriate methods to eliminate them. In this case, preference is given to the simplest methods for implementation, which, in case of failure, will not create insurmountable difficulties for further attempts to provide the necessary mode of operation.

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