

## **Influence of External Wellhead Conditions on Experimental Determined Performance Curves of Steam-Water Geothermal Wells**

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### **ABSTRACT**

The paragraphs should not have line breaks between them – the Normal style will space the paragraphs automatically. Influence of external wellhead conditions on performance curves of steam-water wells is examined. It is established that dependence of external wellhead pressure on flow rate influences the obtained performance curves. The facts of instable operation of wells during exploitation are explained in case when wellhead pressure corresponds to stable operation during testing. Stabilizing effect of throttling by valve during usual testing is noted, which is absent during exploitation. In a result, a well can operate stably at higher wellhead pressure and lower flow rate during the usual testing. Recommendations for receiving of adequate information about the prospects of wells, based on results of usual testing, are presented. Technical solutions to ensure the stability of mode operation of steam-water wells are proposed.

### **1. INTRODUCTION**

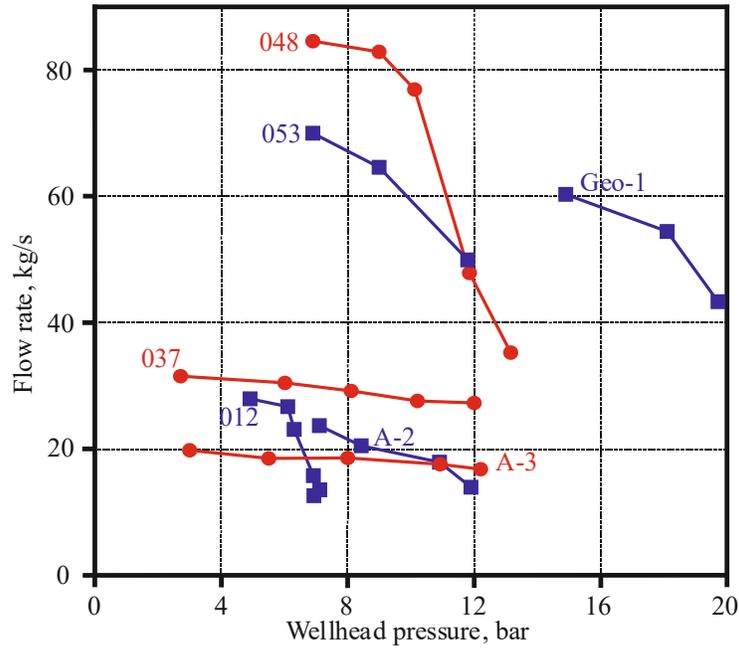
Geothermal energy is one of the renewable energy sources associated with prospective solutions to the world's energy problems and shows a steady development growth (Bertani, 2016; Lund and Boyd, 2016). Achieved volumes of this development no longer correspond to mere subsidization in this field. Drilling takes up significant part of the costs associated with the implementation of geothermal projects; therefore, more topical issue, at present, is the increase in the efficiency of existing wells.

Much attention is paid to the well stimulation (Grubelich et al., 2015; On and Andrino, 2015; Pasikki et al., 2010; Siratovich et al., 2015; etc.). Other ways are developed to improve wells' exploitation (Shulyupin and Chernev, 2015). The possibility of energy production from geothermal fluids without their elevation to the surface has been investigated (Alimonti et al., 2016; Holmberg et al., 2016; Wołoszyn and Gołas, 2016; Lous et al., 2015; etc.). This approach makes it possible to exploit the non-productive wells. However, obtained thermal capacity in this case is less than the values obtained by forced convection in traditional method of well exploitation. More detailed processes are studied that do not have obvious practical application (Pashkevich and Muratov, 2015; Muratov and Pashkevich, 2015), but do have cognitive interest and possible practical application in the future.

The wells of a geothermal field with reservoir fluid temperature over 100°C usually bring to the surface the fluid in state of a steam-water mixture. Often there were cases of unsuccessful commissioning of steam-water wells when results of testing predict a favorable outcome. For example in Mutnovskoe field (Kamchatka), some wells were unable to operate at a wellhead pressure which was acceptable during testing of those wells. Sometimes this can be explained with the time factor, i.e. change of well characteristics from the testing moment to commissioning attempt, but in some other cases, this explanation is not applicable. For example, attempts of commissioning the wells A-2 and A-3 in Mutnovskoe field were made immediately before and after testing. Those wells had stable operation during test (look Fig. 1) in wellhead pressure range of 7.0-11.9 bar and 3.0-12.2 bar, respectively, but those wells were unable to operate with a wellhead pressure of 7.0-7.5 bar.

The main purpose of the well testing is to find a correlation between flow rate and wellhead pressure. Graphical illustration of this correlation is known as the performance curve (output curve). For example, Fig. 1 shows some typical performance curves of wells at Mutnovskoe field. Test results show the basic information about performance capabilities of the wells and the geothermal field in general.

The influence of testing technology for steam-water wells on resulting performance curves is researched in this article. In particular, the phenomenon is studied when the well is stable during testing, but unstable during exploitation at the same wellhead pressure. The research aim is to develop recommendations on obtaining adequate information on well performance capabilities based on the results of their testing.



**Figure 1: Performance curves of some wells in Mutnovskoe field: Well 012 were not capable of providing the necessary pressure for exploitation; wells A-2 and A-3 had difficulties during commissioning; wells 37, 053, 048 and Geo-1 had no difficulties.**

## 2. METHODS FOR PERFORMANCE CURVES CALCULATION

The evidences suggest that if a geothermal well works steady at certain wellhead pressure in one case and does not do the same at the other, some additional conditions should exist, which ensure its steady operation. Evidently those conditions are related to the downstream flow from wellhead. For a long time, there is a permanent interest in the steam-water flow stability of the geothermal wells (Ledinegg, 1938; Boure et al., 1973; Nayak and Vijayan, 2008; Ruspini et al., 2014; etc.). Including, there is interest to the stability of the steam-water flow in the geothermal wells (Droznin, 1980; Shulyupin, 2017). The flow stability in a steam-water well could be defined by the condition (Shulyupin, 2017)

$$\frac{\partial p_w}{\partial G} + \frac{\partial \Delta p_{int}}{\partial G} > 0, \quad (1)$$

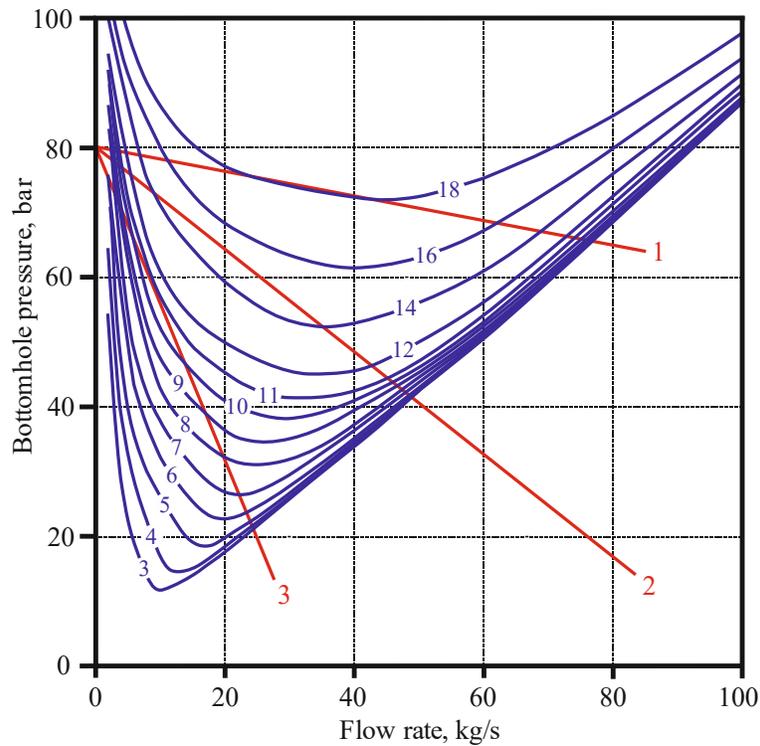
where  $G$  is mass flow rate,  $\Delta p_{int}$  is internal pressure drop (the amount of pressure drop by friction, convective acceleration and gravity),  $p_w$  is wellhead pressure, defined as an external parameter depending on the flow conditions outside the well.

Equality of wellhead pressures during testing and exploitation suggests equality of flow rates in both cases. Respectively, equality of internal pressure drops and their derivatives are expected. Existence of stable flow in one case and unstable flow in other case is explained by difference of values for first term in the left part of inequality (1). In real conditions of exploitation the well works for the collector, or main pipeline, or separator (sometimes group separator). In this equipment, relatively constant pressure is kept, which provides relatively constant wellhead pressure, i.e. the first term of the left part of (1) is close to zero.

Testing is carried out at fixed stages of wellhead pressure. The stages are provided by throttling of the flow at the valve located at the entrance to the flow-measure unit. The flow-measure unit creates a significant pressure drop, which has substantially dependent on the flow rate. In this case the first term in the left part of inequality (1) has essential role and it has positive sign and thus supports stability. Such support explains the fact of improved stability at the testing.

Consider this feature in more detail on the example of average well of Mutnovskoe field. Depth of well to upper boundary of reservoir (feed zones) is 1400 m, inside diameter to depth 1100 m is 0.225 m, lower diameter is 0.152 m. Enthalpy of reservoir fluid is 1200 kJ/kg, static pressure on upper boundary of reservoir is 80 bar.

Considering that the current pressure in the well at the level of the upper border of the reservoir ("bottomhole pressure") consists of wellhead pressure and the corresponding pressure drop in the well, the left part of inequality (1) can be defined as partial derivative of bottomhole pressure on flow rate. Fig. 2 shows graphs of bottomhole pressure depending on flow rate. Bottomhole pressures were calculated with WELL-4 simulator (Shulyupin and Chermoshentseva, 2017). Every graph was calculated at constant wellhead pressure. In area of high flow rate the graphs corresponding to low wellhead pressures are united. It is result of appearance of conditions for critical flow in wellhead.



**Figure 2: Interconnection of bottomhole pressure and flow rate for well and reservoir: well characteristics are blue lines; reservoir characteristics are red lines; wellhead pressures for well characteristics are changed from 3 bar to 18 bar; reservoir characteristics correspond high (1), medium (2) and low (3) performance.**

Fig. 2 also contains reservoir characteristics. Reservoir characteristics are shown with straight lines. It corresponds to stationary flow with a linear filtration law. Operational parameters are determined by intersection of characteristics for well and reservoir. Intersection point is work point. Static bottomhole pressure is accepted as 80 bar. Characteristic 1 is drawn through the point of extremum for wellhead pressure of 18 bar. Having such reservoir characteristic the well corresponds to high-performance wells at the Mutnovskoe geothermal field. Graph 2 is drawn through the point of extremum for wellhead pressure of 14 bars. Having such characteristic the well corresponds to middle-performance wells at the same field. Graph 3 is drawn through the point of extremum for wellhead pressure of 7 bar. Having such characteristic the well corresponds to "problematic" wells at the field. Such wells do not operate with wellhead pressure above 7 bar (work points are absent). It is noted that the above-mentioned wells A-2 and A-3 at the pressure of 7 bar have flow rate that correspond to "problematic" wells (about 20 kg/s, Fig.1 and Fig. 2).

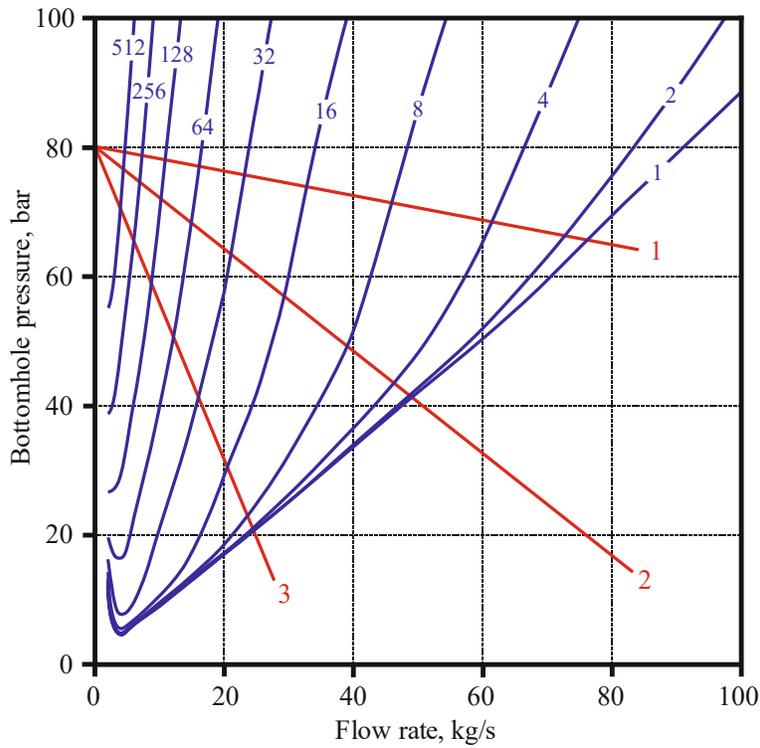
Steam-water mixture comes into the measurement unit in the processes of testing where flow-rate parameters are determined. External environment is usually the atmosphere. Atmospheric pressure is independent on the flow rate. A pressure drop takes place between the wellhead and the external environment. This drop is the result of the hydraulics losses in the unit and throttling valve when setting the wellhead pressure stages. Let this pressure drop has a quadratic dependence on the flow rate

$$p_w = p_{ext} + kaG^2, \quad (2)$$

where  $p_{ext}$  is external pressure,  $k$  is loss coefficient,  $a$  is intermediate coefficient ( $a = 100 \text{ (kg}\cdot\text{m)}^{-1}$ ).

Fig. 3 shows graphs of bottomhole pressure depending on flow rate for external pressure  $10^5 \text{ Pa}$  and wellhead pressure determining by formula (2). Diapason of losses coefficient is 1–512. Bottomhole pressures are calculated with WELL-4 simulator. Graphs of the reservoir are similar to Fig. 2. Calculation of well graphs with the loss coefficient of less than 1 is meaningless. There are signs of critical flow in the wellhead in this case. A further reduction of the loss coefficient stops to influence the flow in the well.

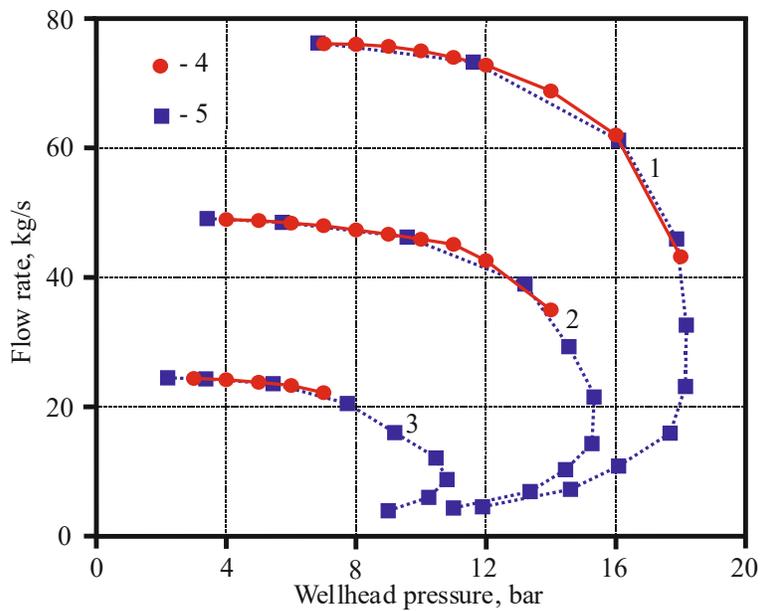
Calculated performance curves of wells are obtained via points of intersection of graphs for well and reservoir. For the graphs shown in Fig. 2, it is possible to build three performance curves, conforming to the reservoir graphs with high, medium and low performance. Those curves correspond to independent wellhead pressure from flow rate. Similar three performance curves can be constructed for Fig. 3. Those curves correspond to dependent wellhead pressure.



**Figure 3: Interconnection of bottomhole pressure and flow rate for well and reservoir: well characteristics are blue lines; reservoir characteristics are red lines; wellhead pressures for well characteristics are determined by formula (2), loss coefficients diapason is 1 to 512; reservoir characteristics correspond high (1), medium (2) and low (3) performance.**

**3. RESULTS**

Fig. 4 shows performance curves constructed for independent wellhead pressure from flow rate (Fig. 2) and dependent wellhead pressure (Fig. 3). Curves for independent wellhead pressure are superimposed on curves for dependent wellhead pressure. Curves for dependent wellhead pressure are shown with dotted lines. These curves have continuation.



**Figure 4: Performance curves for corresponding reservoir characteristics (1), (2) and (3): 4 is work points by Fig. 2; 5 is work points by Fig. 3.**

Performance curves shown in Fig. 4 relate to average well. Real wells at the Mutnovskoe field have variations in design and reservoir conditions. Therefore, absolute similarity for graphs in Fig. 1 and Fig. 4 is absent. In each case, the feature of the real curve can be explained by the peculiarities of the well construction and reservoir conditions.

The curve of the high-performance well is shown in Fig. 4 under number 1. When testing with independent wellhead pressure the curve (solid line) is characterized by a monotonic decrease of flow-rate until 43.3 kg/s when wellhead pressure is increasing flow until 18 bar. At a lower flow rates, as well as at greater pressures the well cannot operate. When testing with dependent wellhead pressure the curve has continuation to the area of more high pressure of up to 18.2 bar for 32 kg/s flow rate. In addition, there is an inversion: transition from an increase to decrease of flow rate when wellhead pressure is decreased.

The curve of medium-performance well is shown in Fig. 4 under number 2. When testing with independent wellhead pressure the curve (solid line) is monotonic. Minimal flow-rate is 35 kg/s, maximal wellhead pressure is 14 bar. When testing with dependent wellhead pressure the curve has continuation to the area of more high pressure of up to 15.3 bar for 20 kg/s flow rate. There is an inversion.

The curve of low-performance well is shown in Fig.4 under number 3. When testing with independent wellhead pressure the curve (solid line) is monotonic. Minimal flow-rate is 22.2 kg/s, maximal wellhead pressure is 7 bar. When testing with dependent wellhead pressure the curve has continuation to the area of more high pressure of up to 10.8 bar for 9 kg/s flow rate.

In some cases the well can have three different states at a fixed wellhead pressure. If the well has the performance curve shown in Fig. 4 under number 2, the wellhead pressure equals 15 bar. The first state corresponds to operation with small throttling; flow rate is 25 kg/s. Second state corresponds to operation with more throttling; flow rate is 13 kg/s. The well is unable to operate in the third state when the wellhead pressure does not depend on flow rate.

#### 4. DISCUSSION

An analysis of curves in Fig. 4 shows, that the performance curves obtained during well testing depend not only on the characteristics of reservoir and well construction, but also on the technology of testing. Throttling of the wellhead is a factor supporting the stability of the flow in the well, and it provides a more complete presentation of the well performance. However, a practical decision about use of the well reasonably to accept on basis of data corresponding to testing with independent wellhead pressure, when it is devoid of the stabilizing effect of throttling.

Testing is a specific process. Testing is always executed with throttling in wellhead. In theory the independent wellhead pressure can be provided during the testing, if the separator method is used for measurement of flow-rate parameters and the separator is big and the throttling is executed after separation, but it is difficult in practice. Large volume of separator is necessary, and the separator must operate at high pressure. It is easier to solve the problem on basis of data corresponding to testing with dependent wellhead pressure. The necessary condition is the second term of the left part of inequality (1) is calculated on the basis of measurement data. Negative sign of calculated term indicates that stable well operation is provided by throttling. In this case the well is unable to operate at independent wellhead pressure.

Inversion of performance curve has specific interest. This phenomenon is provided by stabilizing effect of throttling. For several reasons, the observation of this phenomenon are not so well known. Firstly, the phenomenon does not fit into the traditional view of performance curves. It does not contribute to increased focus on the phenomenon. It is believed that the typical performance curve of steam-water wells does not have an inversion (March, 2015).

Secondly, throttling does not ensure inversion when a large angle of incline of reservoir characteristics takes place. Wellhead pressure increases together with flow rate in down section of inversion performance curve. Wellhead pressure is the difference of bottomhole pressure and internal pressure drop. Consequently, the down section of inversion curve corresponds to condition

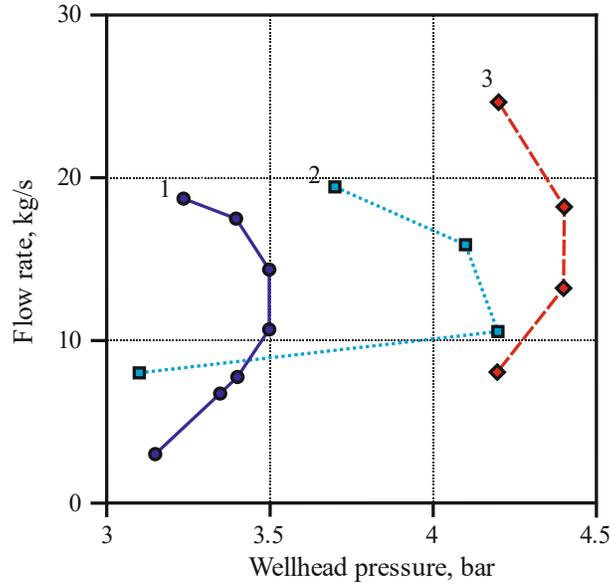
$$\frac{\partial p_b}{\partial G} - \frac{\partial \Delta p_{int}}{\partial G} > 0, \quad (3)$$

where  $p_b$  is bottomhole pressure defined as external parameter which depends on flow conditions in underground reservoir.

The first term of (3) can have large negative value. The second term of (3) cannot always compensate it.

Third, measurement of flow rates during test has limited range. Area of small flow rates has no practical interest, but it is important for inversion. Measurements for small flow rates often are absent. Fourth, flow parameters pulsate and the well often stops to operate at small flow rates. It impedes measurement in inversion area. However, the phenomenon of inversion was observed by the author clearly in practice (Shulyupin, 2017).

Fig. 5 shows empirical performance curves of some wells. These curves were obtained via well testing at the Pauzhetskoe geothermal field (Kamchatka). Flow throttling was used in the test process. Nature of the flow had no fundamental changes in area of the inversion. Thereby, this phenomenon should be regarded as empirically proven.



**Figure 5: Experimental performance curves of some wells in Puzhetskoe geothermal field: 1 – well 108; 2 – well 120; 3 – well 123.**

Figures 2 and 3 show, that extremum point of well graph is lifted when wellhead pressure, or loss coefficient are increased. Minimum flow rate for stability operation corresponds to the case when intersection of well and reservoir graphs takes place in the extremum point. Static level of underground water often is located below the wellhead. It is typical for exploitation wells of largest geothermal fields in Russia (Mutnovskoe and Puzhetskoe fields in Kamchatka). The well is not able to operate when the flow rate is less than the minimum.

Presented results of calculation show that throttling in wellhead increases upper pressure limit of the performance curve. For example, the considered well with low performance has high pressure limit of 10.8 bar when throttling takes place during the testing. But high pressure limit is only 7 bar when wellhead pressure is independent from flow rate during the test.

Obtained results point at engineering solutions for support of stable well exploitation. The main condition is the inadmissibility of a negative value of the derivative of a wellhead pressure in inequality (1). It appears impossible, but it exists in practice. For example, some steam-water mixture pipelines at the Mutnovskoe field have overly large diameters (Shulyupin, 2013). Steam-water mixture from wells is transported to group separators of power plant with pipelines. Auspicious conditions appear to decrease of steam-water mixture density when flow rate is increased in ascending sections of the pipelines. As a result, pressure drop can decrease when flow rate is increased. Decrease of the pressure drop corresponds to a negative value of the derivative of external wellhead pressure. The same effect can appear in descending sections of the pipelines when flow rate growth can increase mixture density.

Artificial increase of pressure drop in the pipeline is one of methods for removal of the instability. It should be noted that that pressure drop on its own is not a stability factor. It is necessary to increase the derivative of external wellhead pressure. Satisfactory results take place by flow throttling in the valve which is mounted in the outlet of the wellhead (Shulyupin and Chernev, 2015). It is easily obtained based on formula (2)

$$\frac{\partial p_w}{\partial G} = \frac{2(p_w - p_{ext})}{G} \tag{4}$$

Flow parameters of steam-water mixture in the Mutnovskoe field were measured until 2004 with well known method of critical discharge (James, 1970; Wibowo et al., 2015; Irsamukhti et al., 2015). In later years, the parameters were measured with separator method ensuring maximal precision (Wormald, 1984). In the process of measurement the mixture is separated at pressure which is close to atmospheric pressure. Necessary stage of wellhead pressure is supported with throttling in the valve between the wellhead and separator.

Throttling generally occurs in regime of critical flow, or critical flow takes place in wellhead when the valve is fully open. Experimental investigations show that flow rate has linear correlation with pressure of critical flow for the first approximation (Shulyupin and Alekseev, 1995). Correlation of pressure in the critical flow and the wellhead is also linear as a first approximation. Then correlation of wellhead pressure with flow rate has linear form for the first approximation

$$p_w = bG, \tag{5}$$

where  $b$  is a coefficient depending on flow enthalpy and the section area of a critical flow.

Wellhead pressure derivative is obtained from formula (5)

$$\frac{\partial p_w}{\partial G} = \frac{p_w}{G}. \quad (6)$$

Taking into consideration the difference of formula (4) and (6) the most effective method in order to provide necessary wellhead pressure stage for every concrete case. This method can use critical or uncritical flow. However, manipulations with equipment do not increase the wellhead pressure infinitely. Fig. (2) shows that wellhead pressure has absolute maximum. Absolute maximal value corresponds to point where reservoir graph must touch the well graph. Calculated with formula (5) the performance curves are not fundamentally different from the curves calculated with formula (2). The difference would affect the ascending sector of curve in the area of minimal flow rates. This area has no practical interest.

Valve throttling is a simple method to support the stable well operation. But this method is not the most effective. It is applied in only some cases and even in these cases this method is not necessary reliable. Specifics of instability development in steam-water well is in its development from wellhead to bottomhole (Shulyupin, 2017). Theoretically the well can operate in metastable regime, when condition (1) is not realized for well in general, but the flow in wellhead satisfies the condition (1). Stabilization of well operation by this method is executed with empirical selection of necessary throttling level. The most likely result of such procedure will be a metastable regime. In this case, there is a high probability of instability of initiation when the pressure in separators and pipelines changes.

The most effective method for the support of stable well operation is the reduction of the internal cross-section of the well. It substantially changes the well graph; extremum point is displaced in the area of low flow rates (Shulyupin and Chernev, 2015). In this case the intersection of well and reservoir graphs takes place in the area of positive value of bottomhole pressure derivative; that is the area of stable operation.

## 5. CONCLUSIONS

The main conclusions of the present work are:

- 1) The testing technology influences the first term in the left part of inequality (1). The stable well operation at a specified pressure during testing process does not guarantee stable operation with the same pressure during exploitation.
- 2) When testing with valve throttling it is advisable to determine section of performance curve corresponding to testing at independent external wellhead pressure. This section determines permissible diapason of wellhead pressure at exploitation.
- 3) Steam-water mixture transporting from wells is inadmissible in conditions corresponding to a negative value of the partial derivative of external wellhead pressure by flow rate.
- 4) The most effective method for supporting stable well operation is the reduction of the internal cross-section of the well.

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