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REVIEW

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Some methods for reducing of steam deficit at geothermal power plants exploitation: experience of Kamchatka (Russia)

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Abstract

Experiences in the use of methods for reducing steam deficit in operating geothermal power plants in Kamchatka (Russia) are summarized. Methods which are able to increase the steam flow rate of existing wells are considered: stimulation of flow to the well by multiple air injections and by quick opening of wellhead; stabilization of operating regime via throttle on the wellhead; stabilization of the well's operating regime via reduced inside diameter; optimization of steam gathering scheme (together with water, separately and combined); reduction of hydraulic losses during transportation of steam; reduction of scaling by mixing flows from different wells; exception of steam loss during well's flow parameters measurement.

Keywords: Power plant, Steam deficit, Geothermal well, Feed zone, Pipeline, Steam–water mixture, Wellhead pressure, Flow rate

Background

Global energy development is characterized by dynamic and steady growth in installed capacity of geothermal power plants (Bertani 2015). Experience shows that productive wells, over time, reduce flow rate, and sooner or later all plants are faced with steam deficits.

Geothermal power engineering in Russia is presented with five plants: three are located on the Kamchatka Peninsula, the other two are located on Kuril islands. Over the last 20 years, electricity production from geothermal resources has developed without adequate support from academic institutions and foundations. Embedded in practice, innovations were often based on engineering intuition; their rationale was developed later, sometimes limited to hypothesis.

This paper summarizes experiences with certain methods to reduce steam deficit in operating the geothermal power plants of Kamchatka, where more than 90 % of installed capacity of Russia's geothermal power generation is concentrated at the Mutnovskoe and Pauzhetskoe fields. Only original methods (or methods which proposed to be original at the time) are considered. The methods are divided into two groups: one involves exploitation of previously unconditioned wells and the other an increase in steam flow rate by modifying the gathering system.

Steam deficit at geothermal power plants of Kamchatka

Three geothermal power plants operate on the Kamchatka Peninsula: Pauzhetskoe (constructed in 1966, installed capacity as of now 14.5 MWe), Verkhne-Mutnovskoe (1999, 12 MWe) and Mutnovskoe-1 (2003, 50 MWe). The first plant is located at the Pauzhetskoe field. The other two are located at the Mutnovskoe field. The Pauzhetskoe plant provides stand-alone energy sector and operates at variable power. Mutnovskoe's plants supply central energy sector (Petropavlovsk-Kamchatsky and other nearby towns). They operate in conjunction with other types of power plants, producing up to 25 % of the energy for that sector.

In order to select the most effective methods to reduce steam deficit, it is important to detect the origins of its occurrence. Deficit can be caused by: depletion of geothermal reservoir resources; reduction in performance of the equipment, including wells; and increase in consumer activity.

Russia's practice in the development of geothermal fields avoided miscalculations in geothermal reservoirs resources. Therefore, the above-mentioned first origin—the depletion of geothermal resources—fortunately, is not relevant. However, all operating plants of Kamchatka have faced the problem of steam deficit.

A decrease in performance of wells is presented on the Mutnovskoe field. This decrease is associated mainly with scaling in filtration channels that feed underground reservoirs and wells trunks (scaling in the trunks of wells established experimentally).

The Pauzhetskoe plant has a surplus of installed capacity. For many years, there were significant reserves in productive wells, the last of which was drilled in the 1970s. Currently, the reserve is exhausted. In Pauzhetskoe area, there was an increased demand for electricity due to the resurgence of the fishing industry and the use of modern, energy-intensive fish processing technologies. The increase in electricity demand induces steam deficit when a surplus of installed capacity and lack of productive wells are present.

The use of unconditioned wells

Stimulation of flow to the well

The Mutnovskoe and Pauzhetskoe fields have geothermal reservoirs with fluids mainly in a liquid state. Water levels in wells located below the surface of the earth are static. A feature of Russia's approach in determining a reservoir's resource is the physical delivery of necessary steam flow rate to the surface. The decision to build the plant is made only after sufficient evidence exists that the derived steam flow rate does not fall below the required level during operation. A large number of wells are drilled during the process of field exploration. Experience shows that not all drilled wells have required exploitation characteristics. Sometimes, the wells are not able to function. Some wells spontaneously stall during exploitation. In some cases, there is a pulse operating regime. The attempts to use previously unproductive wells by stimulation of flow to the well bottom have been made when engineers were faced with a steam deficit at Mutnovskoe field.

One of the effective methods of stimulation is the multiple displacement of water column from the well into reservoir. A compressor pumps air to the well. Air displaces water from the well in the reservoir. Then the wellhead is sealed; displaced water in the reservoir is heated. Then the wellhead quickly opens with special valve and the boiling water rises through the well. The boiling decreases the density of fluid in the well. The decrease in density induces a lifting mechanism. This mechanism is called "steam-lift". Abrupt changes of temperature and pressure increase the permeability of the feed zone. Flow to the bottom of the well is stimulated. Note that the most productive well at Russia's geothermal fields (Well 042 of Mutnovskoe field) previously had been considered unproductive and was re-introduced into operation via the above described technology. The presented method is simple in practice. It can be recommended as a first attempt of well stimulation. Then, other methods (Pasikki et al. 2010) may be considered.

Stabilization of the operating regime via throttle on the wellhead

The instability in a well's operation can be caused by transients in underground geothermal reservoirs, including the bottom zone, and in the system of transportation and consumption of steam. Also, instability can be caused by transients in the well itself. The major cause of instability that most often prevents normal operation is considered to be a mismatch between the potential feed zones and a disproportionately large diameter of the well (Frolov et al. 1964). In this case, there has been a lack of throughput capacity of well with its feed zones.

Consider the mechanism of this instability in an example of comparison of characteristics of well and throughput capacity of feed zones. As the well characteristic, take the interconnection of bottom pressure and flow rate at a constant outlet pressure (Fig. 1). The descending branch of the well characteristic is the dominance of the gravitational component of pressure losses in two-phase flow. This component is decreased when flow rate is increased. The ascending branch is characterized by the dominance of components on friction and acceleration.

As the feed zones characteristic, take the linear interconnection of bottom pressure and flow rate. The working point is the intersection of characteristics. Multiple variants of the characteristics of feed zones are possible. The well is not capable to operate in the case of characteristic 4.

Consider the well operating at characteristics 2 and 3. Stability of the system is provided via a mechanism which compensates fluctuations of flow parameters. Analyzing the instability of the system, as determined by external factors, the development of

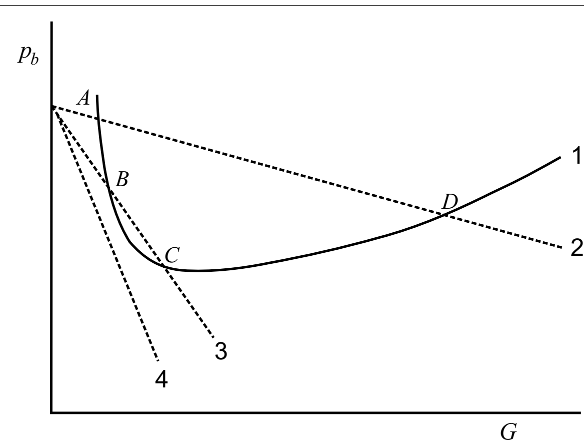

Fig. 1 Interconnection of bottom pressure (p_b) and flow rate (G): 1 is characteristic of well at a constant head pressure; 2, 3, 4 are variants of feed zones characteristics

fluctuations at the input and output should be considered. The main parameter determining the dynamics of the process is pressure. Outlet pressure is constant corresponding to the condition. A wide range of possibilities for the occurrence of internal instability in two-phase flow implies the existence of pressure fluctuations at the bottom. An increase of bottom pressure reduces inflow to the well in accordance with feed zone characteristic. Flow rate reduction in positive derivative of well characteristic (point *D*, Fig. 1) reduces bottom pressure, i.e., the fluctuation is compensated. Flow rate reduction increases bottom pressure in the area of negative derivative of well characteristic, i.e., the fluctuation is growing. The development of fluctuation at point *C* is damped; at points *A* and *B*, it is increased.

Introduce stability criteria as a ratio of characteristics derivatives for the well and feed zones

$$S = \left(\partial p_{\mathrm{b}} / \partial G\right)_{\mathrm{s}} / \left(\partial p_{\mathrm{b}} / \partial G\right)_{\mathrm{r}}$$

where S is stability criteria, p_{b} is bottom pressure, G mass flow rate, $(\partial p_{\mathrm{b}}/\partial G)_{\mathrm{s}}$ is derivative of well characteristic, $(\partial p_{\mathrm{b}}/\partial G)_{\mathrm{r}}$ is derivative of feed zones characteristic. In accordance with the mechanism, stability conditions are: $S < 0$ is stable regime (point *D*, compensated fluctuation), $0 < S > 1$ is unstable regime (point *C*, damped fluctuation), $S > 1$ is extremely unstable regime (points *A* and *B*, increased fluctuation). The existence of a positive angle characteristic of feed zones is hypothetical. In practice, there is only a negative angle of the characteristic. In this case, a positive value of well characteristic derivative can be seen as the requirement for stability.

Condition of constant pressure is independent of flow rate. It is important to note that this condition is not implemented at the wellhead. Between the head and the environment with constant pressure, there are elements that create incremental resistance. Even with the natural flow measured, wellhead pressure is quite different from atmospheric (barometric), especially in critical flow regime, when there is a pressure drop at a transfer through critical cross section.

For example, the relative constancy of pressure in Mutnovskoe field is provided in the plant's group separators; the steam–water mixture goes through the elements of the wellhead equipment and pipeline, sometimes more than 2 km long. When wells are being tested, the atmosphere is usually the environment with constant pressure. The measuring equipment is between the wellhead and the atmosphere. A change in wellhead pressure is executed via throttling on the wellhead valve. An analysis of stability of the system should be carried out taking into account additional resistance between the wellhead and the environment with constant pressure.

Consider the well characteristic taking into account the existence of additional equipment installed between the wellhead and the environment with constant pressure, with well parameters: inside diameter of 0.2 m, depth of 800 m and mixture enthalpy of 800 kJ/kg. Additional equipment is characterized with total coefficient of local resistance. The outlet pressure would be 1 bar.

The MODEL simulator is used for the calculation of additional resistance pressure drop. The simulator is intended for hydraulic calculations of steam–water mixture transfer (Shulyupin 2007, 2013). The WELL-4 simulator is used for the calculation of the pressure drop from the bottom to the wellhead (Shulyupin and Chermoshentseva 2013).

Obtained characteristics are presented in Fig. 2, when total coefficient of local resistance is 0, 5, 10, 20, 40 and 100 (increase of coefficient can be interpreted as decrease in throat of operating wellhead valve). Point 0 derivative is marked with a cross.

In case of feed zones characteristic 1, an increase of additional resistance stabilizes a well's operation if additional resistance coefficient is 20 and above. The well has the unstable mode when the additional resistance coefficients 0 and 5 were unsustainable. Therefore, an increase in the additional resistance, hence the wellhead pressure, is the factor stabilizing well's operating regime.

It is noted, that it is not a simple increase in wellhead pressure. This is an increase of wellhead pressure via additional resistance. For example, the working point (situated at the point of intersection of characteristics) corresponds to stable flow for coefficient resistance 20 in Fig. 2. Wellhead pressure is 1.54 bars according to calculations at the point. The characteristic of the well is represented in Fig. 3 (curve number 2) at a constant specified pressure in the wellhead. In this case, the working point is in an unstable area. Increasing wellhead pressure is crucial. Increasing wellhead pressure by an increase of environment pressure (which is independent from flow rate) has a different result. Additional resistance supports equilibrium of the system via change of the wellhead pressure at flow rate change.

Instability of flow has occurred in three wells of Mutnovskoe field. Those are Wells 4-E, A-2 and A-3. The steam–water mixture from the wells arrives in plant's group separator. The wells are located close to the plant; pipelines of steam–water mixture have a large diameter and minimum hydraulic resistance, i.e., the pressure in the wellhead, in practice, is determined by pressure in the separator. The pipelines have plots, including vertical, with a very large diameter that does not satisfy the condition of stable operation (Shulyupin 2007). In these pipelines, the pressure drop can be increased by reducing the flow rate. This reaction of the pipeline is the destabilizing factor for the system. A simple

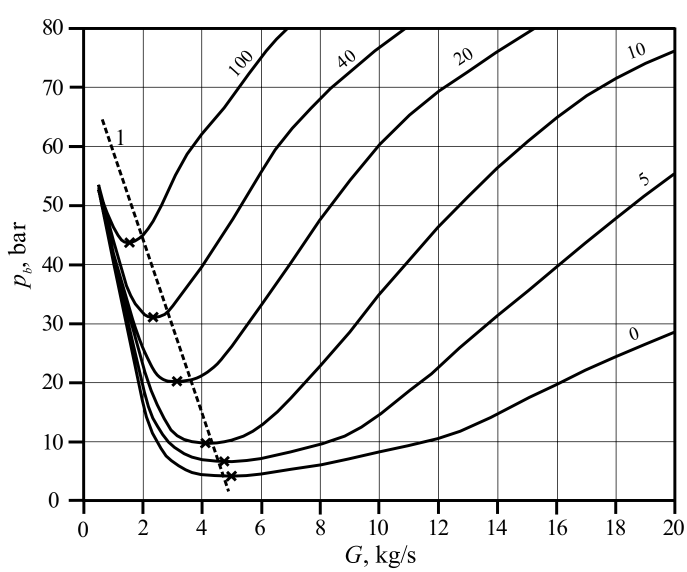

Fig. 2 Characteristics of well with additional resistance coefficients of 0, 5, 10, 20, 40, 100. 1 is characteristic of feed zones

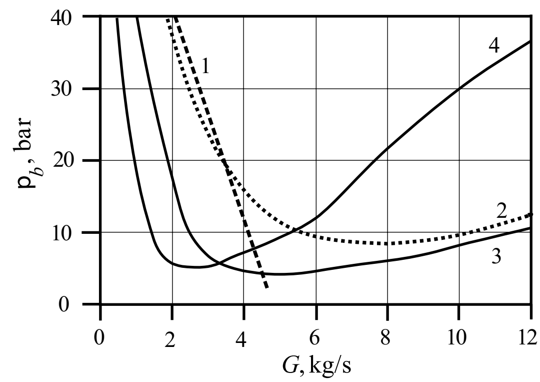

Fig. 3 Characteristics of feed zones (*1*) and wells: diameter of 0.2 m with wellhead pressure 1.54 bars (*2*) and 1 bar (*3*); diameter of 0.15 m with wellhead pressure 1 bar (*4*)

throttle of flow by wellhead valve has stabilized the operation of Wells 4-E and A-3. Pressure drop in the valves was about 2 bars. Well A-2 was operating at a low maximum pressure that is not allowed to apply throttling.

Reduction of well's inside diameter as a method of stabilizing its operating regime

Well A-2 periodically failed during operation. Thermal stress accompanying change in regime of operation created a gap in the well's sealing. The well ceased to be productive after 10 years of exploitation. In order to seal the gap, the installation of a pipe inside the well with a smaller diameter was considered. Calculations showed the possibility of increasing the maximum operating pressure of this well (Shulyupin and Chermoshentseva 2013). Therefore, a practical change in well design does make it possible to increase the maximum operating pressure and achieve stability of operating regime without throttling.

Consider the changing characteristics of the well with decreased inner diameter to illustrate this effect (Fig. 3). The figure shows the characteristics of the well (depth 800 m, enthalpy 800 kJ/kg, wellhead pressure 1 bar) with inner diameter of 0.2 and 0.15 m. Reduction of inner diameter transfers the 0 derivative point in the direction of the lower flow rate and increases the stability of the well's operating regime.

Modification of steam gathering system

Optimization of steam gathering scheme

Selecting the scheme for gathering the heat agent from wellhead to a plant is a key issue. It determines many subsequent decisions. The heat agent can be transported by pipeline in the condition of steam–water mixture or in one-phase condition when separation takes place near the wellhead. As a result, gathering schemes of steam and water can either be joint or separate. Also, a scheme can be combined with an intermediate separation plant (usually for group of wells), or with gathering of the heat agent from different wells for a different scheme. Each of the schemes has its advantages and disadvantages.

The main advantages of the joint scheme are minimizing equipment for gathering system, and getting the maximum quantity of steam per unit of produced mixture. Its weaknesses are large pressure loss and complexity of measuring a well's flow rate. The main advantages of the separate scheme are a small pressure drop that ensures maximum well's flow rates. Its weakness is the difficulty of separated water transport. The separate scheme was adopted in the Pauzhetskoe field. The joint scheme was adopted in the Mutnovskoe field. Experience shows that the combined scheme allows advantages of both, so it should be most effective. As a result, in time, elements of the combined scheme appeared on both of these fields. For example, a mixture of Well 131 at the Pauzhetskoe field is transported by steam–water pipeline at distance of 400 m to by separated in a convenient location. Steam gathering systems from Wells 042, 053 and 013 at the Mutnovskoe field have an intermediate separation to reduce the amount of water in the plant separator.

Adoption of the joint scheme for the Mutnovskoe field was a result of the combination of circumstances. First, the combined scheme was designed similar to the steam gathering scheme in the Ohaaki field (Wigly 1989); where the mixture comes from wells to the separator plant, and afterwards the plant's steam and water are transported separately. Then, the concept of modular development of the field was adopted: the individual power plants were to be installed on individual groups of wells. Transport of steam–water mixture is not planned for distances over 500 m. Complexities of joint transportation were not relevant for this decision. The final project of Mutnovskoe plants consisted of long pipelines of steam–water mixture, but the complexity of this scheme by analogy with previous design had not been considered. Built during the construction of the plants, the steam–water pipelines were designed without the proper hydraulic calculation. Operation has shown that, in some cases, the mistakes were made in the selection of diameter for the pipelines. A small diameter led to essential pressure loss (more 2 bar/km). The inflated diameter led to stratification of the flow; liquid plugs were formed in rising sections and pulsations were created. Pipelines contained elements with great resistance, such as U-shaped compensators of thermal expansions. Hydraulic calculation of steam–water mixture pipelines in Kamchatka came to be used only after 2003 for construction of new pipelines and reconstruction of old ones.

Consideration of all solutions for optimization of steam gathering scheme in Kamchatka's geothermal plants is believed not to be reasonable. However, similar challenges are solved with success in many other fields (Zhao et al. 2000; Umanzor et al. 2015). For example, a comparison of three options is presented for the concrete case of steam and water transportation: two-phase flow and two different configurations of two line—the first with one steam flow line, the other with water flow; the second with one steam flow line and the other with water flow when water pipeline is inside of steam pipeline (Ghaderi 2010). Only the method of partial separation may be worth mentioning (Shulyupin 2007). Separation on the wellhead reduces pressure drop in the pipeline's steam transportation, lowers the wellhead pressure and increases the flow rate of the well. Values of wellhead pressure and flow rate changes depend on the interconnection between flow rate and the wellhead pressure of the real well, enthalpy of mixture, transportation distance and so on. In some cases, this can increase the flow rate of supplied steam to turbines. For example, separation on the wellhead for Well 042 of the Mutnovskoe field reduces pressure drop during transport by 2.0 bars; consequently, wellhead pressure is reduced by 2.0 bars, well flow rate increases by 7.5 kg/s (for the mixture), and steam flow rate in the plant increases by 1.0 kg/s. Coarse separation is appropriate in this case. First, it simplifies the separation process; second, lower water content can reduce hydraulic resistance during the transportation of steam.

The Mutnovskoe field offers experience in small-size separator usage (designed by D.P. Usachev). This separator adds a geothermal separator line (Zarrouk and Purnanto 2015) in design and purpose. Horizontal flow of the mixture is swirled along the axis of motion prior to entering the separator tank (Fig. 4). The pipe has a gap through which the water-enriched mixture is discharged into the tank. Steam continues moving horizontally. Gravity separation is realized in the tank.

A well's performance determines the possibility of positive effects when using partial separation. In each case, the usefulness of this method should be considered separately.

Reduction of hydraulic losses during transportation of steam

As already noted above, lowering hydraulic losses in the gathering system allows the reduction of wellhead pressure and increasing a well's flow rate. Lowering hydraulic losses in the Mutnovskoe field has been realized with the replacement of U-shaped compensators (expansion unit) on the bellows (a U-shaped compensator has a resistance coefficient eight times that of a bellows expansion joint), flattening of pipelines (to reduce the overall length of pipelines and exclude local resistance at turning of flow), dismantling non-functional valves, etc. Lowering the hydraulic losses in Pauzhetskoe field was also realized with the improvement of transportation conditions to the separator, change of separators type, and redistribution of the flow rate among the main steam pipelines.

A method for evaluating flow rate increase when hydraulic losses are lowered is described Shulyupin et al. (2015). After evaluating possible changes to flow rate, new values must be verified according to the stability criteria described in "Stabilization of the operating regime via throttle on the wellhead" section. Reducing hydraulic resistance is pointless if the new value does not conform to the positive derivative of the well characteristic and instead of increasing flow rate, it may result in an unstable regime of the well's operation.

Recent plans for modification of steam gathering system to reduce the hydraulic resistance has been developed in the Mutnovskoe and Pauzhetskoe fields. Each plan is being evaluated for its effectiveness with the most effective ones having already been

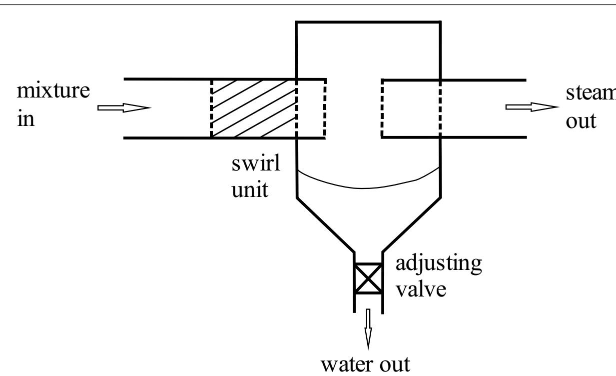

Fig. 4 Separator designed by D.P. Usachev

implemented. For example, Well 029 W of Mutnovskoe field saw reconstruction of the pipeline to plant: U-shaped compensators have been replaced and flow control unit has been dismantled. This increased the flow of steam to the plant to 2.3 kg/s.

Reduction of scaling

The productive wells of the Pauzhetskoe and Mutnovskoe fields mainly discovered water feed zones. Only two wells of Mutnovskoe field discovered the "steam cap" zones of the geothermal reservoir. Steam transportation from those two wells is accompanied by heavy scaling. This increases the hydraulic resistance. Our experience shows that mixing of flows from those wells with flows from steam–water wells prevents scaling.

Steam loss during measurement of well's flow rate

In Russia, rules for exploitation of geothermal fields require regular measuring of flow rate of steam and water from each production well. Execution of this requirement is difficult in case of joint transportation of water and steam. Orifice method was developed to support the two-phase transportation at the Mutnovskoe field (Shulyupin and Alekseev 1995). Steam flow rate is determined by the pressure difference on the orifice. Phase composition of mixture is determined by the ratio of dynamic pressure to pressure difference on the orifice. The desire to simplify the plant's building excluded this method from the project.

Currently, the well's mixture parameters at Mutnovskoe field are measured with the separation method. The separator is moved from one testing well to another. Well flow is transferred to the separator while pipeline to plant is closed at the time of testing. The complexity of the climate limits the time period for testing. As a result, each well is tested approximately once every 2 years.

Switching the flow to separator leads to loss of steam for the plant. In addition, the operating regime is broken. The new regime can differ from the operating regime. Steam loss, the issue of adequacy and desire to reduce time between measurements is forcing us to research other measurement methods.

The orifice creates a noticeable pressure drop. Its use is inappropriate when there is steam deficit, except where there is a need to create a pressure differential to stabilize the operating regime of the well. A method of pressure tube (Pitot's tube) was proposed Shulyupin et al. (2012) as an alternative to the orifice, in which steam flow rate is determined by down-stream dynamic pressure and phase composition is determined by ratio of down-stream and up-stream dynamic pressures. However, this method also has its drawbacks. Dynamic pressure is comparable with pulsation amplitude in steam–water mixture pipelines. Dynamic pressure has more pressure pulsations at the wellhead, but profiles of velocity and phase composition is uncertain. Therefore, the question of the most appropriate method for flow rate measurement of wells in Mutnovskoe field has not been definitively resolved.

Possibilities of research funding in industrial organizations is limited. However, the research for development of suitable methods for flow rate measurements of production wells is planned to be continued.

Conclusions

Engineers of Kamchatka have some experience on the reduction of steam deficit in geothermal power plants. This experience has been gained over many years. Increase of steam flow rate from wells can be achieved by involving previously non-productive wells. Also, increase of steam flow rate can result in modification of steam gathering systems. Increase of steam flow rate is possible by various methods:

- stimulation of flow to the well by multiple air injections followed by quick opening;
- stabilization of operating regime via throttle on the wellhead;
- stabilization of the well's operating regime via reduced inside diameter;
- optimization of steam gathering scheme (together with water, separately and combined);
- reduction of hydraulic losses during transportation of steam;
- reduction of scaling by mixing flows from different wells;
- exception of steam loss during well's flow parameters measurement.

Authors' contributions
Both authors have made equally substantive intellectual contributions to the article. Both authors read and approved the final manuscript.

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Competing interests
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References

Bertani R (2015) Geothermal power generation in the world 2010–2014. Update report. In: Proceedings of the World Geothermal Congress, 2015. Melbourne, Australia, no. 01001.

Frolov NM, Averjev VV, Dukhin IE, Lyubimova EA. Methodical recommendations for study of thermal waters in wells. Moscow: Nedra; 1964.

Ghaderi I (2010) Comprehensive comparison between transmission two-phase flow in one line and two line separately for 50 MWe power plant in Sabalan, Iran. In: Proceedings of the World Geothermal Congress, 2010. Bali, Indonesia, no. 2501.

Pasikki RG, Libert F, Yoshioka K, Leonard R (2010) Well stimulation techniques applied at the salak geothermal field. In: Proceedings of the World Geothermal Congress, 2010. Bali, Indonesia, no. 2274.

Shulyupin A, Alekseev V. Testing of steam–water wells. In: Proceedings of the World Geothermal Congress, 1995, vol. 3. Florence; 1995. p. 1835–37.

Shulyupin A, Lyubin A, Chernev I (2015) Prediction of geothermal well performance in case of modification of steam gathering system. In: Proceedings of the World Geothermal Congress, 2015. Melbourne Australia, no. 25026.

Shulyupin AN. Hydraulic calculations for the transport of a steam–water heat carrier at hydrothermal fields. J Volcanol Seismol. 2013;7(3):196–203. doi:10.1134/S0742046313030068.

Shulyupin AN. Efficiency of partial water removal during transmission of steam–water mixture on geothermal fields. J Volcanol Seismol. 2007;1(5):328–32. doi:10.1134/S0742046307050053.

Shulyupin AN, Chermoshentseva AA. On calculation of a steam–water flow in a geothermal well. Tech Phys. 2013;58(8):1100–5. doi:10.1134/S1063784213080227.

Shulyupin AN, Parshin BE, Chernev II. Measurement of discharge parameters of a well in exploitation of geothermal fields with two-phase transport of heat carrier. Meas Tech. 2012;54(11):1242–8. doi:10.1007/s11018-012-9888-z.

Umanzor C, Hall F, Buchanan R, Rosaria N (2015) Piping Design Considerations for Geothermal Steamfields. In: Proceedings of the World Geothermal Congress, 2015. Melbourne, Australia, no. 25027.

Wigly DM (1989) Separation plant and pipework design—Ohaaki steam field. In: Proceedings of the 11-th New Zealand Geothermal Workshop. p. 19–24.
Zarrouk SL, Purnanto MH. Geothermal steam–water separators: design overview. Geothermics. 2015;53:236–54.
Zhao HD, Lee KC, Freeston DH (2000) Geothermal two-phase flow in horizontal pipes. Proceedings of the World Geothermal Congress, 2000. Kyushu-Tohoku, p. 3349–3353.