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Steam-water flow instability in geothermal wells

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ABSTRACT

The phenomenon of steam-water flow instability in geothermal well based on Newton's second law is considered. The factor causing instability is the reduction of gravitational force that counteracts with an increase in flow rate, resulting in a decrease of mixture density with increasing flow rate. External pressure can effectively influence the stability in case of sufficiently rapid response to changes of flow rate. The specific of the development of instability in the geothermal well does not assume a sufficiently rapid reaction of bottom-hole pressure. In other words, bottom-hole pressure reaction cannot ensure flow stability. Reaction of wellhead pressure can be a stabilizing factor. The example of a typical well of Pauzhetka geothermal field shows, that inversion of output curves is associated with the stabilizing effect of the additional hydraulic resistance at the outlet. It is noted, that wells have extended sections with internal instability, which may be the source of oscillation of flow parameters.

1. Introduction

The heat of the Earth is one of the types of renewable energy resources, which may be associated with a solution of global energy problems of the future. It is noted, that there is a steady growth in the volume of usage of geothermal resources (Bertani [1], Lund and Boyd [2]). This process is accompanied by reduced role of subsidies in development of geothermal projects. Modern geothermal power engineering, in many parts of the world, develops in equal competitive environment. Indeed, in Kamchatka (Russia), geothermal power engineering withstands competition even through competitors are subsidized (Kolesnikov et al. [3]).

The expenses associated with drilling of wells take up significant part in geothermal projects. Therefore, efficient use of wells' stock potential is a key to self-sufficiency. In recent years, many publications have been devoted to stimulation of wells' potential, with Pasikki et al. [4], On and Andrino [5], Grubelich et al. [6], Siratovich et al. [7] and other publications. Technologies of borehole heat exchanger evolve (Lous et al. [8], Woloszyn et al. [9] and other publications). However, the problem of instability of flow in steam-water wells, which are the main supplier of heat agent to geothermal power plants, remains without adequate attention. It is shown that there are methods to ensure the stable operation mode, allowing economize by drilling of new wells in the works of Shulyupin and Chernev [10].

As shown in review by Ruspini et al. [11], there are many manifestations of two-phase flow instabilities. Productive steam-water well has to operate in a stable mode. From practical point of view, the instability presents an interest in case of negative impact on operation of the well. Such instability is discussed in this article.

2. Mechanism of instability

2.1. Stability condition

Let's consider the movement of some element located in the channel between cross-sections with the distance Δz. Using Newton's second law for this element, we obtain the equation of motion in projections on the z-axis

$$\frac{\partial G}{\partial t} = \frac{p_1}{\Delta z} - \frac{p_2}{\Delta z} - f_f - f_c - f_g, \tag{1}$$

where G – mass flow rate, p_1– pressure in lower cross-sections of element, p_2 – pressure in upper cross sections of element, f_f – internal friction force divided by volume measures, f_c – inertia force due to convective acceleration divided by volume measures, f_g – gravitational force divided by volume measures.

The left side of the equation expresses non-stationary change of momentum; right side expresses the sum force acting on the element. A disturbance in the form of increased momentum (or increased mass flow rate) will not have development if increase of mass flow rate reduces the sum force, this reduce can be interpreted as the increase in forces preventing increase in momentum. A disturbance in the form of increased momentum would break the flow stability if the summary force increases in the case of mass

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Nomenclature

G	mass flow rate
p	pressure
f	force divided by volume measures
Δp	pressure drop
Δz	distance between considered sections
k	resistance coefficient of measuring unit

Subscripts

f	corresponded to internal friction
c	corresponded to convective acceleration
g	corresponded to gravitation
ext	external
int	internal
1	lower section of considered element (down hole for all well)
2	overhead section of considered element (wellhead for all well)

Greek letter

ρ	density

Dimensionless number

a	stability parameter

flow rate increase. Therefore, the stability condition is the negative partial derivative of the right side of Eq. (1)

$$\frac{\partial}{\partial G}\left(\frac{p_1}{\Delta z}-\frac{p_2}{\Delta z}-f_f-f_c-f_g\right)<0. \tag{2}$$

Eq. (1) has actuality at zero left side if condition (2) is satisfied.

In the right side of Eq. (1) the first two terms characterize external forces and three last terms describe the forces acting inside of the element. Therefore,

$$p_1-p_2=\Delta p_{ext}, \tag{3}$$

$$\text{and } (f_f+f_c+f_g)\Delta z=\Delta p_{int}, \tag{4}$$

where Δp_{ext} and Δp_{int} – external and internal pressure drop.

Taking into account above notation we can present the stability condition as

$$\frac{\partial \Delta p_{\text{int}}}{\partial G}>\frac{\partial \Delta p_{ext}}{\partial G}, \tag{5}$$

Inequality (5) is well known as stability condition when considering Ledinegg instability [11]. Classic Ledinegg instability [12] is associated with characteristic of friction and phase transition caused by the heat flow on the channel wall. The instability of flow in steam-water geothermal well is caused by other factors.

Typically, the well is a vertical pipe; rarely, it has a complicated geometry with the upper vertical part and the inclined bottom part. In reality, the right side of inequality (5) for whole of the well (where Δz is entire length of the well) is always less than zero. Therefore, a special interest is the case when,

$$\frac{\partial \Delta p_{\text{int}}}{\partial G}>0. \tag{6}$$

In this case, the flow has internal stability and can exists under constant external conditions (p_1 and p_2 are constants). If in the considered element $\Delta z \to 0$, condition (6) can be presented in a differential form,

$$\frac{\partial}{\partial G}\left(-\frac{\partial p}{\partial z}\right)>0. \tag{7}$$

Implementation of condition (6) for entire well corresponds to stable mode of operation. In real conditions the effect of friction force and convective inertia increase when flow rate increases. But the growth of flow rate enhances a mixing of phases, ratio of average velocities of phases is reduced, consequently mixture density is reduced. Due to this, gravity force is reduced. Therefore, violation of condition (5) can manifest due to small influence of friction and acceleration. In this case, the decisive factor for manifestations of instability is the gravitational force, and reinforcing factor is the phase transition at decompression that further reducing density of the mixture. And thus this case can be classified as the gravitational instability of steam-water flow.

2.2. Graphic interpretation of the stability conditions in the geothermal well

Fig. 1 shows the dependencies of external and internal pressure differential from bottom-hole to wellhead at Pauzhetka (Kamchatka, Russia) field typical well. Parameters of the well: inner diameter – 0.2 m, depth – 800 m, mixture enthalpy 800 kJ/kg, pressure at wellhead – 3 bars (constant). The curve for the internal differential was calculated with WELL-4 model [13]. Descending branch (on the left) of the curve for internal pressure differential is characterized by the dominance of the gravitational component of pressure differential in two-phase flow, which decreases with increased flow rate. Ascending branch (on the right) is characterized by the dominance of the components of friction and convective acceleration that increases with increased flow rate.

Dependence of the external pressure drop to the flow rate is shown with straight lines. One line corresponds to the condition of independence of flow rate from external pressure drop. Second line corresponds to typical condition of well feeding at Pauzhetka field. The first point corresponds to the typical value of bottom-

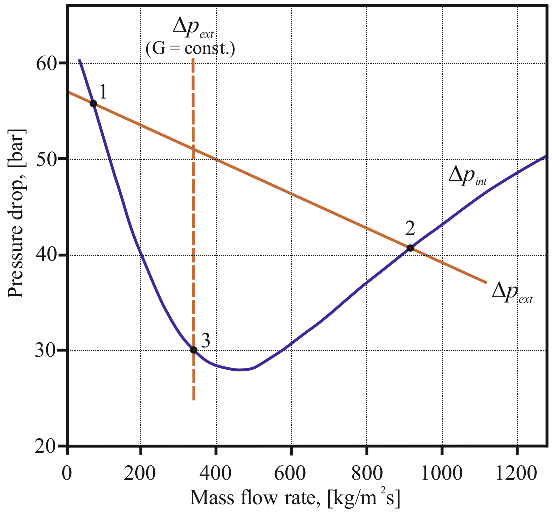

Fig. 1. Internal and external pressure drop vs. flow-rate characteristic curves for steam-water geothermal well.