PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

The Increase Energy Efficiency of Circulating Geothermal Systems

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Keywords: geothermal circulating systems, energy efficiency, airlift.

ABSTRACT

The results of calculation estimates of exergy expenditure in different ways of water lifting in circulating geothermal system are presented. Higher efficiency of air-gaslift technique as compared with pumping operation methods is demonstrated.

Reservoir pressure and well production rate are decreased under the condition of the prolonged operation period of geothermal field. Wells are transferred from the gushing forth mode into the pump operation one; later on the portion of pressure wells, and in the final operation period all pressure wells are transferred into the operational well mode. To increase the operational efficiency of a geothermal fields the transfer from the extensive gushing technology to the intensive circulating one is required with the increase in the operational-well output by 3-5 times by means of forced lifting of geothermal water and lowering the heat production cost by 1.5-2 times.

1. THE PURPORSE OF THE WORK

Analysis of different technological schemes of geothermal water lifting in the operational well to increase the output and ate quantity of heat being extracted.

2. THE PUMP OPERATION MODE

The main obstacle for a wide transition from the gushing forth technology to the circulating one with natural collectors is an insufficient efficiency of the available means of the forced geothermal heat-carrier lifting without which neither real circulations not positive economic results can be obtained due to excessive leakages and low gushing output (Boguslavsky, 1984; Dyadkin, 1989; Muraev, 1973; Zorkshin, 1974). The searches of creating high-productive means of the forced lifting the geothermal heat-carrier are being done.

The optimal output of operational wells is about 300-400 m3/h taking into account the expenses on boring operation, well arranging and operational expenditures (mainly and pump electricity) (Dyakin, 1989). The well output can be 30-70 m^3/h when using Ukraine made pumps and about 200-300 m^3/h when using some foreign samples.

Centrifugal artesian pumps are used for deep pumping out geothermal water. The ultimate water lifting height at maximum supply is not more than100-150 m and at the same time the installation of an upper 300 mm – diameter casing pipe is required. The artesian turbine pumps with up to 70 m^3/h supply can be used when well diameters are 200-250 mm.

For example, (Vogel Pumpen), Loware (Italy) pumps provide the nominal output of 80 l/s (288 m^3/h) and the head of 250 m with the set engine capacity of 318 kW. However, to install it the well diameter should be increased up to 13" (325 mm) that will lead to more expensive boring operations.

3. THE AIRLIFT OPERATION MODE

The increase in the gushing-forth mode period of the geothermal well operation is possible by means of air or gas supply into the well being operated. When supplying gas into the well being operated a gas-liquid mixture is formed which density is less than the water one that leads to the well output increase at a given pressure difference between the bed water pressure and the well month one. The energy of compressed air (or gas) being in so much determined by the mixer immersion depth (the device for gas input into the flow of a droplet liquid) allows to change head pressure characteristics of the operational well and provide the increase in its airlifting capacity (discharge capacity).

4. THE TECHNIQUE OF THE AIRLIFT CALCULATION

The equation of vertical upward steady-state motion of two component slugging flow is the following:

$$-\frac{dp(z)}{dz} = \frac{4\cdot\tau_{mix}(z)}{D} + \frac{d}{dz}\left\{G''(z)\cdot w''(z)\cdot\varphi(z) + G'(z)\cdot w'(z)\cdot\left[1-\varphi(z)\right]\right\} + \rho_{mix}(z)\cdot g \qquad (1)$$

where *p(z)* is the pressure in the pipe section at a distance z from the mixer; *τ(z)* is the shearing stress; *D* the lift-pipe diameter; *w'(z)* and *w"(z)* are real liquid and gas velocities; *G'(z)* and *G"(z)* are mass liquid and gas velocity respectively; *φ(z)* is an actual gas content of the water-air mixture; *g*–free drop acceleration.

Mass velocities of the gaseous *G'' (z)* liquid *G'(z)* phases are equal to respectively, taking into account the motion continuity equation:

$$G''(z) = \frac{Q_{air} \cdot \rho''_0}{\omega \cdot \varphi(z)} = \frac{G \cdot x}{\varphi(z)} \tag{2}$$

$$G'(z) = \frac{Q_{airlift} \cdot \rho_0}{\omega \cdot [1 - \varphi(z)]} = \frac{G \cdot (1 - x)}{1 - \varphi(z)} \tag{3}$$

where *Qair* is the volumetric flow-rate of air (gas) under normal conditions; *Qairlift* is volumetric airlift supply; *w* a cross-section of a lifting pipe; p_0'' air density under normal conditions; p' water density; *x* a mass flow-rate gas content; *G* is mass velocity of a water-air mixture.

Mixture density $p_{mix}(z)$ in a separate flow model is described by the equation:

$$p_{mix}(z) = w(z) \cdot \rho''(z) + [1 - \varphi(z)] \cdot \rho' \tag{4}$$

Taking into account that the mass velocity of the water-air mixture G is a constant value, the equation (1) will be:

$$-\frac{dp(z)}{dz} = \frac{4 \cdot \tau_{mix}(z)}{D} + G \cdot \frac{d}{dz}[x \cdot w''(z) + (1 - x) \cdot w'(z)] + \{\varphi(z) \cdot \rho''(z) + [1 - \varphi(z)] \cdot \rho'(z)\} \cdot g \tag{5}$$

Actual phase velocities in the lifting pipe:
a) water

$$w' = \frac{Q_{airlift}}{w \cdot [1 - \varphi(z)]} \tag{6}$$

b) air

$$w''(z) = \frac{Q_{air}(z)}{w \cdot \varphi(z)} \tag{7}$$

Assuming the pressure change linearity along the lifting pipe height and integrating the equation (5) for an airlift lifting-pipe section having the length z_i (where $0 \le z_i \le H+h$, where *H* is the airlift lifting height, *h* is geometrical mixer immersion), we obtain the equation:

$$p_{mix} \cdot \frac{z_i}{H + h} = \frac{4}{D} \int_0^z \tau_{mix}(z) dz + G[x \cdot w''(z) + (1 - x) \cdot w'(z)]\Big|_0^z + g \int_0^z \{\varphi(z) \cdot p''(z) + [1 - \varphi(z)] \cdot p'\} dz \tag{8}$$

which can be given in the following way:

$$\partial_{\Sigma_i} = \partial_{f_i} + \partial_{a_i} + \partial_{gi} \tag{9}$$

Where $\partial_{\Sigma i}$ is the total pressure difference in the lifting pipe section having the length z_i:

$$\partial_{\Sigma i} = \partial_{mix} \cdot \frac{z_i}{H + h} \tag{10}$$

∂_{fi} is the pressure difference in the lifting pipe section having the length z_i due to the friction:

$$\partial_{f_i} = \frac{4}{D} \int_0^z \tau_{mix}(z) dz \tag{11}$$

∂_{ai} is the pressure difference in the lifting pipe section having the length z_i due to the acceleration:

$$\partial_{a_i} = G \cdot [x \cdot w''(z) + (1 - x) \cdot w'(z)]\Big|_0^z \tag{12}$$

∂_{gi} is the pressure difference in the lifting pipe section having the length z_i due to the gravity:

$$\partial_{g_i} = g \int_0^z \{\varphi(z) \cdot \rho''(z) + [1 - \varphi(z)] \cdot \rho'\} dz \tag{13}$$

Shearing stresses τ and actual gas contents φ are calculated by empirical equations (Kononenko, 2007).
The total power required for the loss compensation through friction, acceleration and a gravitational component when the water air flow moves along a vertical lifting pipe section with the z_i- length having an average volumetric flow-rate $Q_{f.r.}$ is determined by the equation:

$$N_{\Sigma_i} = P_{\Sigma_i} Q_{f.r.} = P_{mix} \frac{G \omega}{H + h} \int_0^z \frac{dz}{P_{mix}(z)} \tag{14}$$

The power required for the friction loss compensation is:

$$N_{f_i} = \partial_{f_i} \cdot Q_{f.r_i} = \frac{4 \cdot G \cdot \omega}{D \cdot z_i} \cdot \int_0^z \tau_{mix}(z)dz \cdot \int_0^z \frac{dz}{P_{mix}(z)} \tag{15}$$

The power required for the acceleration loss compensation is:

$$N_{a_i} = \partial_{a_i} \cdot Q_{a_i} = \left[x \cdot w''(z) + (1-x) \cdot w'(z)\right]\Big|_0^z \cdot \frac{G^2 \cdot \omega}{z_i} \cdot \int_0^z \frac{dz}{P_{mix}(z)} \tag{16}$$

The power required to overcome the gravity is:

$$N_{g_i} = \partial_{g_i} \cdot Q_{g_i} = g \cdot \frac{G \cdot \omega}{z_i} \cdot \int_0^z P_{mix}(z)dz \cdot \int_0^z \frac{dz}{P_{mix}(z)} \tag{17}$$

The total power (18) is summed up with the components (15), (16), and (17).

$$N_{\Sigma i} = N_{f_i} + N_{a_i} + N_{g_i} \tag{18}$$

The power to the z_i long-pipe section is supplied by the compressed air flow:

$$N_i'' = \partial_0 \cdot Q_{air} \cdot \ln \frac{\partial_0 + \partial_{mix}}{\partial_0 + \partial_{mix} \cdot \left(1 - \frac{z_i}{H+h}\right)} \tag{19}$$

where p_0 is the atmospheric pressure; p_{mix} is the excessive pressure in the mixer.
The power supplied to the lifting pipe by the water flow is:

$$N' = \partial_{mix} \cdot Q_{airlift} \tag{20}$$

The power required for the loss compensation through phase sliding when the water-air flow moves is:

$$N_{slip\ i} = N_{s_i} - N_{\Sigma_i} \tag{21}$$

where N_s is the power supplied by the water-air flow:

$$N_s = N_i'' + N' \tag{22}$$

The calculation of the equations (1)-(22) is done (22) by the numerical method according to the program developed (Zorkshin, 1974).

5. MAIN RESULTS

The calculations are carried out using initial data: the air flow-rate at under normal conditions Q_a m^3/min is 0.1-10; the lifting pipe diameter D, m is 0.146, 0.246; the lifting pipe length $H+h$, m is 205-505; the water lift height H, m is 5-55; the equivalent pipe roughness Δ is 0.0002; the geometrical mixer immersion h, m is 200; the operational –pipe diameter, m is 0.146, 0.246; the operational pipe length, m is 1595; shearing stresses are calculated by the Armanda-Navstrueva formula and the actual gas content is done by the Armanda one.

Thermal and physical air and water parameters are the following: water and air densities are 1000 and 1.2 kg/m^3, respectively; the dynamic water viscosity is $1 \cdot 10^{-3}$ Pa/s; the dynamic air viscosity is $1.79 \cdot 10^{-5}$; the surface strain coefficient is 0.0723 H/m.

The decrease in pressure along the water air mixture motion in the air-lifting pipe results in the increase in the volumetric air flow-rate and corresponding changes of the volumetric flow-rate and actual gas content and flow component velocity. The article (Novokhatsky, 1983) support the permissible validity of the linear law of gas and the liquid-flow pressure change in the vertical pipe. The analysis of hydrodynamic parameters of the water-air flow and its components is fulfilled in the chosen sections of the lifting pipe (along the lifting pipe height $H+h$) with every given air flow-rate Q.

5. THE ANALYSIS OF THE RESULTS

Calculation results of the water-air mixture parameters in the well having the diameter of 0.146 m and the lifting pipe length $H+h$=205 m and geometrical mixture immersion h=200 m with the air flow-rate change from 0.1 to 1.0 m^3/min are given as an example below. The volumetric flow-rate gas content increases from β=0.025-0.030 at the mixture level (z=0) to β=0.28-0.34 at the level of the lifting pipe outlet (z=1, where $z=z/(H+h)$) (Fig.1). The actual gas content due to phase sliding is of a lower value than the flow-rate one and is equal to φ=0.015 at z=0 and φ=0.15-0.218 at z=1 consequence of the phase sliding (Fig.1).

The density of the gas–liquid mixture decreases from ρ_{mix}=991.5–980.2 kg/m^3 at z=0 to ρ_{mix}=848.4–714.1 kg/m^3 at $z=H+h$=205 m due to the air expansion along the lifting pipe height. The dimensionless function $\rho=f(z)$ is constructed for the base value of the mixture density (Fig.2) being equal to ρ_{mix}=980.2 kg/m^3, and dimensionless – density values of the water-air mixture range from ρ=1.0–0.72. The given water velocity in the lifting pipe is of the constant value along the whole pipe length and is w'=0.45–1.9 m/s. The given air velocity increases from w''=0.0045–0.05 m/s at z=0 to w''=0.1–0.99 m/s at $z=H+h$=205 m, and the given mixture velocity changes from w=0.45–1.95 m/s at z=0 to w=0.55–2.1 m/s at z=H+h=205 m. The actual water velocity along the whole lifting pipe length is less than the given mixture velocity w and is equal to w'=0.45–1.94 m/s at z=0 and w'=0.53–2.66 m/s at z=H+h=205 m. The actual water velocity is layer than the given mixture velocity *w* and is equal to w''=0.54–2.35 m/s at z=0 and w''=0.66-3.49 m/s at $z=H+h$=205 m, respectively.

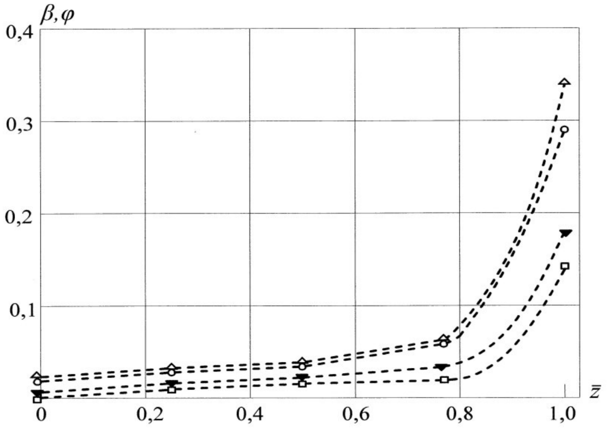

Figure 1: The change of the air content along the airlift lifting-pipe height (the base value z=205 m): ▼, Δ is the volumetric flow-rate gas content *β=f(z)*; □, ○ is the actual gas content *φ=f(z)* (▼, □ –Q_a=0.1 m^3/min; Δ, ○ –Q_a=1.0 m^3/min)

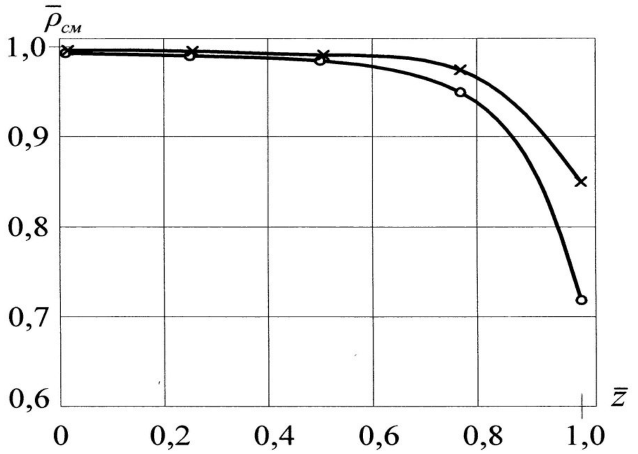

Figure 2: The change of the relative water-air mixture density along the airlift lifting-pipe height p_{mix}=*f(z)* (base value z=205 m, ρ_{mix}=980.2 kg/m^3; × –Q_a=0.1 m^3/min; ○ – Q_a=1.0 m^3/min)

When making dimensionless functions $\overline{w'_0} = f(\overline{z})$, $\overline{w''_0} = f(\overline{z})$, $\overline{w_{см}} = f(\overline{z})$, $\overline{w'} = f(\overline{z})$, $\overline{w''} = f(\overline{z})$ the value of the given water velocity, being equal to $w'_0 = 0.45\ m / s$ is taken as a base one (Fig. 3)

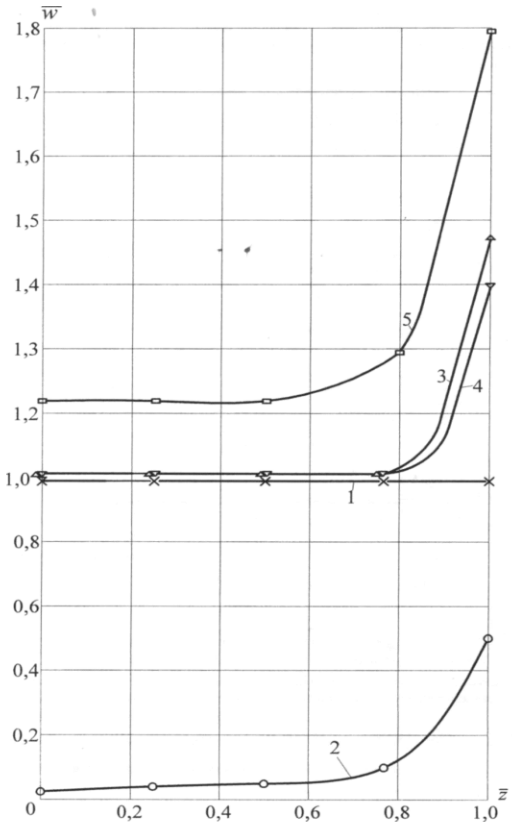

Figure 3: The change of the relative water-air mixture velocities and its components along the airlift lifting pipe height: 1 is a given water velocity; 2 is a given air velocity; 3 is a given water-air mixture velocity; 4 is an actual water velocity; 5 is an actual air velocity; base values z=205 m, w'_0=0.45 m/s

The value of the actual water velocity at the lifting pipe outlet determines the dynamical stresses from the air separator and is a base value when calculating its longevity.

When making the mathematical model of the airlift operation process the assumption concerning the linear change in the total pressure δ_Σ along the lifting pipe height is taken. In fact, the total pressure components due to the gravity δ_g, friction δ_f and acceleration δ_a are linearly as well. When making dimensionless functions $\overline{\delta} = f(\overline{z})$, $\overline{\delta_g} = f(\overline{z})$, $\overline{\delta_f} = f(\overline{z})$, $\overline{\delta_a} = f(\overline{z})$ (Fig. 4) the total pressure value, being equal to δ_Σ=19.9 kgs/sm^2 (1.95 MPa) is taken as a base one.

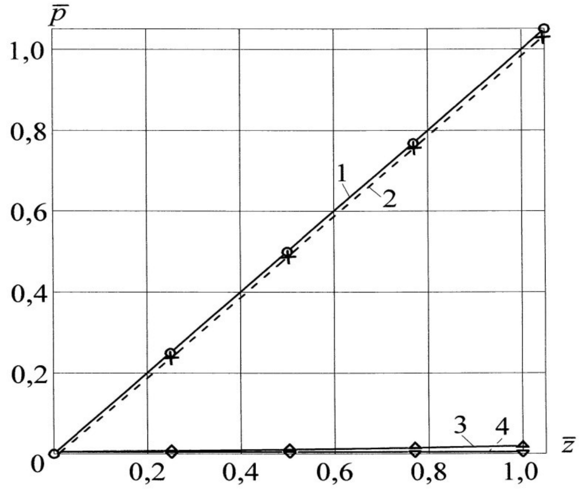

Figure 4: The change of relative pressures along the airlift lifting pipe height:
1–$\delta_\Sigma = f(\bar{z})$; 2–$\delta_g = f(\bar{z})$; 3–$\delta_f = f(\bar{z})$; $\delta_a = f(\bar{z})$ (base values of *z*=205 m, *δ*=19.9 kgf/sm^2 (1.95 MPa)

The total supplied power is monotonously increased from N_p=62.4 kW at z=0 to N_p =67.3 kW at $z=H+h$=205. The power supplied to the lifting pipe by the water flow is defined by the airlift supply, by geometrical system immersion and supplying pipe resistance and is N'=62.4 kW. The power supplied by the compressed air increases due to the pressure difference increase from N''=0 at z=0 to N''=4.98 kW at $z=H+h$=205m.

When making dimensionless functions (Fig. 5) $\overline{N_p} = f(\overline{z})$, $\overline{N'} = f(\overline{z})$ $\overline{N''} = f(\overline{z})$, $N_\Sigma = f(\overline{z})$ the total supplied power value being equal to N_p =67.3 kW is taken as a base one.

Increasing monotonously along the lifting pipe, height powers are changed as well:

a) a gravity compensating value is $N_g =0$ at z=0, N_g=64.3 kW at $z=H+h$=205 m;

b) a friction loss compensating value is N_f=0 at z=0, N_f=2.09 kW at $z=H+h$=205 m;

c) a acceleration loss compensating value is– $N_a=0$ at z=0, N_a=2.09 kW at $z=H+h$=205 m.

The quantitative pressure and power distributions of the slugging gas-water flow for the fulfilled variants of well calculations are: $\overline{p_g} = 60 - 80\,\%$, $\overline{p_f} = 25 - 40\,\%$, $\overline{p_a} = <4\%$, $\overline{N_g} = 15 - 60\,\%$, $\overline{N_f} = 5 - 25\,\%$, $\overline{N_a} = <3\%$, $\overline{N_\Sigma} = 15 - 75\,\%$.

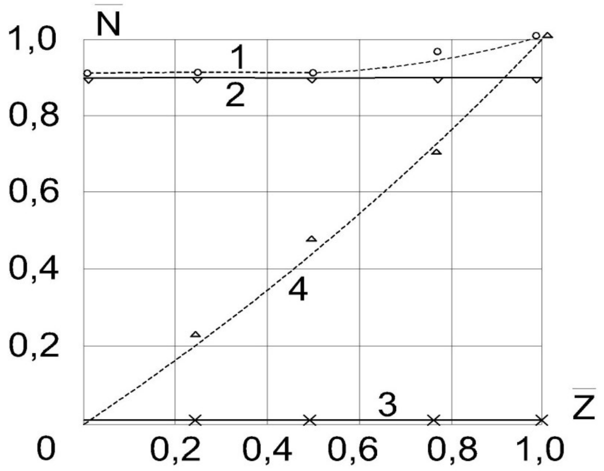

Figure 5: The change of relative powers along the airlift lifting pipe height:
1 – $\overline{N_h} = f(\overline{z})$ **; 2 –** $\overline{N'} = f(\overline{z})$ **; 3 –** $\overline{N''} = f(\overline{z})$ **; 4 –** $\overline{N_\Sigma} = f(\overline{z})$
(base values of z=205 m, N_f=67.3 kW)

The analysis of flow-rate well characteristics with the 146 mm diameter at the airlift operation showed the following: the change of the air flow-rate from 0.1 to 1.0 m^3/min allowed increasing the well output up to 120 m^3/h with the mixture depth of 200 m and lift height of 5 m. The well output decreases up to 25 m^3/h with the increase of the water lift height up to 55 m and with decrease of the mixer immersion depth up to 150 m and the well output is about 40 m^3/h with the mixer immersion depth of 175 m and the water lift height of 30 m. The increase in the air flow –rate up to 8-10 m^3/min provides the increase of the well output with the 146 mm diameter up to 200-225 m^3/h. The well output increases with the increases of its diameter up to 246 mm when other conditions are the same. Thus, the well output increases up to 400-525 m^3/h at the mixer immersion depth of 200 m, the water lift height of 5 m and the air flow rate of 4-5 m^3/min (Fig.6).

6. THE GAS LIFTING OPERATION MODE

The articles (Dyadkin, 1989; Muraev, 1973) present the perspective ideas concerning the use of liquefied easily boiling gas (carbonic acid, freon, isobutene, etc.) instead of air when it is introduced into the liquid the mixture is formed and as far as it lifts upward it forms emulsifying and slugging flow structures that provide significant outputs in the lifting pipe.

An abrupt lifting productivity increase at the installation of water airlift-lifting using two-phase foam (an addition of 0.1% sulpanole) was observed according to (Dyadkin, 1989). Using the foam excludes irrational modes of the water-air mixture motion such as circular (film) as well as provides the corrosive equipment protection.

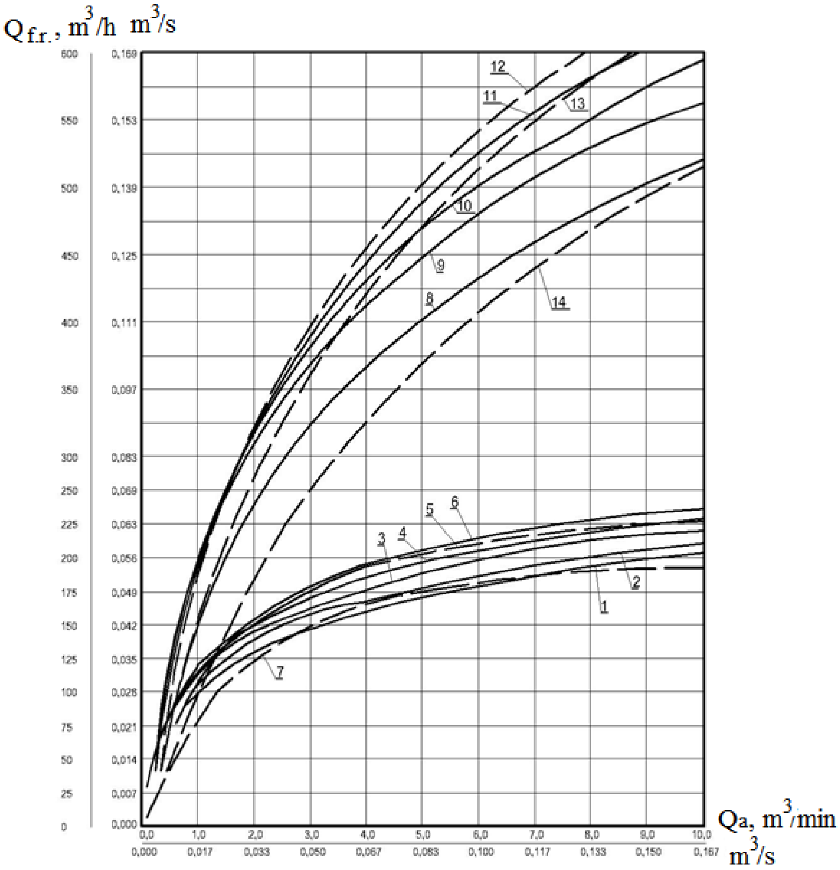

Figure 6: Well output in the function of air flow – rate: a – *D* =146 mm; *H* = 5 m: 1 – *h* = 500 m; 2 – *h* = 400 m; 3 – *h* = 300 m; 4 – *h* = 200 m; 5 – *h* = 100 m; 6 – *h* = 50 m; 7 – *h* = 20 m; b) *D* =246 mm; *H* = 5 m: 8 – *h* = 505 m; 9 – *h* = 405 m; 10 – *h* = 305 m; 11 – *h* = 205 m; 12 – *h* 105 m; 13 – *h* = 55 m; 14 – *h* = 25 m.

The article (Muraev, 1973) indicates that to increase the Geo thermoelectric plant efficiency the scheme with working medium boiling directly inside the operational well operating in gaslift mode was developed. The possibility of low boiling liquid circulation from GCS with vapour formation owing to heat exchange with hot rocks is not excluded.

The article (Muraev, 1973) presents the data concerning laboratory investigation on a gas-liquid mixture structure. Highly refined structures are formed when gas oozes from solution. The results of the laboratory investigations showed that preparation of the saturated carbonic acid solution in water had resulted in forming highly refined emulsion structures with its subsequent introduction into the lifter without using dispersing means.

The article (Novokhatsky, 1983) studied self-circulating systems of heating buildings and cooling the units with high heat emission by an easily boiling heat-carrier. This work highlights the technological scheme of a gas lift system with the circulation of the easily-boiling heat carrier (Fig.7) in the lifting pipe. The system operates in the following way: liquefied gas is supplied into the well being operated up to a required height through the sinking pipe by means of a proportioning pump. The liquefied gas is solved in the geothermal water and when lifting it evaporates forming the vapor-air mixture that provides water lifting. Gas separation from water is done in the separator. Then gas is cooled and condensed in the condenser and is again supplied into the operating well by means of a proportioning pump. Condensation heat is extended either into the heating system or the hot water supply system. The change of the thermodynamic parameters of the liquefied gas when if moves in the closed system is shown in fig.8. The developed closed cycle (1-2-3-4) characterizes the efficiency of the thermodynamic pump providing water lifting in the gaslift system.

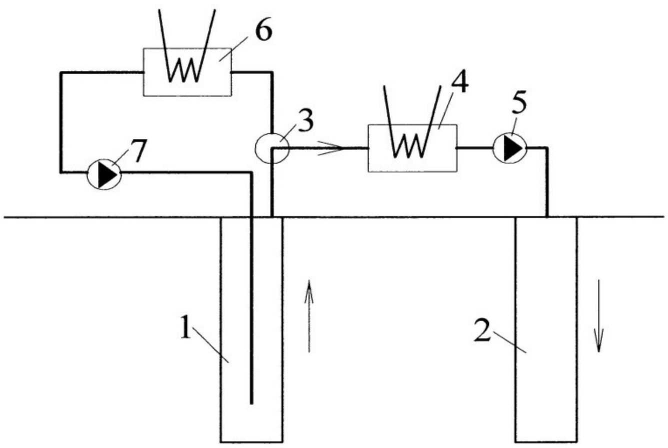

Figure 7: Technological scheme of gaslift water lifting with liquefied gas; 1.2 are operational and input wells, respectively; 3 is a separator; 4 is a heat exchanger; 5,7 are pumps; 6 is a condenser

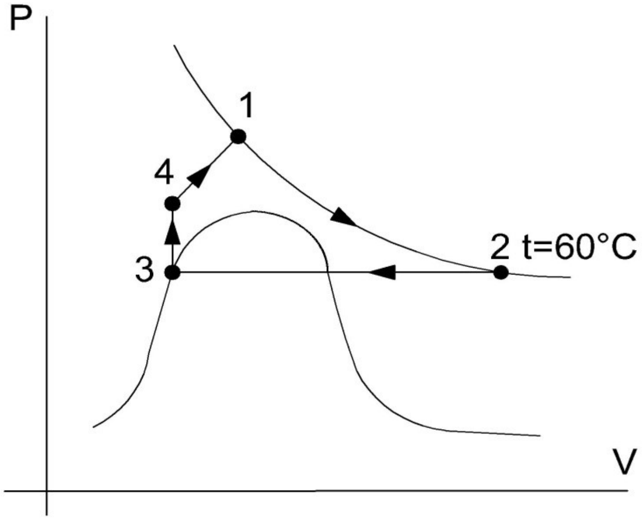

Figure 8: Change of thermodynamic parameters of easily boiling heat-carrier in the circulating system

In the cycle given the process 1-2 is isothermal expansion of a low temperature heat carrier when it moves from the input point to the well mouth, 2-3 is the process of isobar heat-carrier cooling and condensation, 3-4 is the process of compression in the proportioning pump; 4-1 heat-carrier compression when it moves to the input point.

The calculation of hydraulic gas lift modes is done according to the airlift calculation technique. Liquefied gas is supposed to boil instantaneously or in a small section of a lifting pipe.

The comparison of well – operation pump and air-gas lift modes allows to claim that the gas lift mode is characterized by significantly less power expenses and mainly determined by the fixed proportioning pump power that is less than compressor one in the technological system and the proportioning pump with capacity in the pump technology.

Thus, to provide geothermal water output of about 300 m^3/h (80 l/s) the compressor should generate the power of 180-200 kW and the capacity of 4-5 m^3/min while the required proportioning pump capacity and its fixed power can be considerably lowered (by several times).

. CONCLUSIONS

Thus analyzing the results of the fulfilled calculations concerning power characteristics of water lifting means in the technological systems of extracting the geothermal energy. One can note envisaging future of using the air-gas lift technology, particularly with the liquefied gas circulation in it providing the water output increase by 2.5-5 times and the decrease in energy expenses.

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