Thermodynamic Efficiency of Geothermal Plants with Hydrogen Steam Superheating

S.P. Malyshenko, A.I. Schastlivtsev

Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010
Parallel Sessions Book 6: Stationary Applications / Transportation Applications
Proceedings of the WHEC, May 16.-21. 2010, Essen
Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-6
Institute of Energy Research - Fuel Cells (IEF-3)
Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010
ISBN: 978-3-89336-656-9

Thermodynamic Efficiency of Geothermal Plants with Hydrogen Steam Superheating

S.P. Malyshenko, **A.I. Schastlivtsev**, Joint Institute for High Temperatures RAS, Russia

Abstract

Results of the thermodynamic analysis of using hydrogen for steam overheating in geothermal power plants are presented. It is shown that increase of parameters of wet geothermal steam leads to increase in power station efficiency at 3-6 % taking into account expenses of the electric power for hydrogen and oxygen production in electrolyzers. The method of an estimation of increase in efficiency geothermal turbine with growth of parameters of steam and results of calculation of expenses of the electric power is resulted. The optimum overheat range of the geothermal steam for providing maximum geothermal station efficiency is defined at the minimum expenses for installation of the additional equipment. Approximate cost of the additional equipment for maintenance of an overheat is estimated and its pay-back terms are calculated.

1 Introduction

The use of geothermal energy makes possible to get electricity and heat usage of fossil fuels. However, the electrical efficiency of modern geothermal plants is still relatively low (12-18%) primarily due to the parameters where the coolant temperature does not exceed 550 K. The basis of conversion of geothermal heat into electricity is the steam-turbine technology, which is the most effective and affordable in this case. Let consider the main components of the electric efficiency of any single-turbine plant:

1. Thermal efficiency of steam-turbine cycle
    a. turbines on the superheated steam (about 60%);
    b. geothermal steam turbine (about 28%);
2. Efficiency of steam turbine;
    a. turbines on the superheated steam (about 90%);
    b. geothermal steam turbine (about 80%);

Thus, the maximum electrical efficiency of modern single-turbine plant is about 53%, and geothermal plant is only 14-18%.

2 The Problem Formulation

To improve the efficiency of geothermal power plant operating in Rankine cycle is necessary to increase enthalpy drop on the turbine. This could be achieved by increasing the steam parameters at the turbine inlet and lowering outlet pressure. Thus to significantly increase the efficiency of the power unit it is needful to replace the geothermal turbine with the high internal efficiency turbine operating at superheated steam with additional superheating of wet steam.

For superheating of steam it is intended to use high temperature steam produced by combustion of hydrogen in oxygen, which are preliminary obtained by electrolysis. Main flow of wet steam is directly mixed with very high temperature (up to 1700 ˚C) steam from hydrogen-oxygen steam generator working at stoichiometric mixture of components. This technique significantly simplifies the design of superheater and minimizes heat losses [2,3].

3 Thermal Efficiency Analysis of Geothermal Plant with Hydrogen Superheating

An absolute internal efficiency is composed of turbine thermal cycle efficiency and internal efficiency of the turbine. The expression for the single-geothermal power plant with a hydrogen-oxygen steam superheating for the cycle shown in Fig. 1:

$$\eta_i = \frac{G_S \cdot (1+\alpha) \cdot H_{3'-4'} \cdot \eta'_{0i} - \dfrac{N_{H2}}{\eta el}}{Q_{1-2-3} + Q_{3-3'} - Q_{4'-1}} \tag{1}$$

where G_s - steam flow to the turbine without superheating, α - the relative share of high-temperature steam from the added hydrogen steam generator, $H_{3'-4'}$ - enthalpy drop of process 3'-4', η'_{0i} - internal efficiency of the turbine, η_{el} - the efficiency of the electrolyzer, Q_{1-2-3}, $Q_{3-3'}$, $Q_{4'-1}$ – heat supplied and removed.

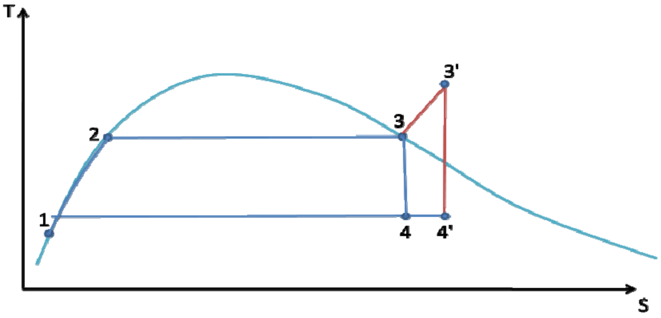

Figure 1: Geothermal power plant cycle with hydrogen-oxygen superheated steam before the turbine.

To determine the internal efficiency of the turbine with the change of steam humidity use well-known relation [4]:

$$\eta'_{0i} = \eta^0{}_{0i} \cdot \chi_{av}' \tag{2}$$

where η^0_{0i} - maximum internal efficiency of the steam turbine, χ'_{av} - the average steam dryness in the steam turbine.

From the condition of energy balance, let us write the expression for the determination of additional work, obtained in the implementation of superheat steam, taking into account the power consumption (PC) of electrolysis:

$$\Delta W = \eta'_{0i} \cdot H_{3'-4'} - H_{3-4} \cdot \eta_{0i} - \alpha \cdot q_p^h \frac{1}{\eta_{el}} \qquad (3)$$

where H_{3-4} –heat drop without superheating, η_{0i} - internal efficiency of the turbine without superheating.

Typical values η^0_{0i} of wet steam turbines for geothermal power plants are 0.75-0.85, for the calculation we take it equal to 0.8. Substituting the data in (1) and (3) for different values of α we obtain the results presented in Table 1.

Installing the upgraded turbines in superheated steam, one makes η^0_{0i} equal to 0.89-0.9. It should also be taken into account that the efficiency of the turbine at superheating steam at operation on wet steam is smaller than the original, because of none-nominal operation mode. The change of the efficiency of geothermal plants by installing turbines on the superheated steam is shown in Table 1.

Table 1

α	**T, K**	**χ'_4, %**	**η'_{0i}, %**	**η_i, %, at η^0_{0i}=0,8**	**η_i, %, at η^0_{0i}=0,9**	**ΔW/W, at η^0_{0i}=0,9**
0	473	12,2	73	14.5	12.8	0
$1 \cdot 10^{-3}$	477	11.9	73.2	14.0	14,6	0,05
$5 \cdot 10^{-3}$	492	10.8	74.1	12.7	17,7	0,2
$7 \cdot 10^{-3}$	500	10.1	75.3	10.1	15,4	0,12
$1 \cdot 10^{-2}$	513	8,7	74,5	8,3	14.7	0,06
$1.5 \cdot 10^{-2}$	535	7,3	75,8	7,5	11.6	-0,16
$2 \cdot 10^{-2}$	557	6.1	76,3	3,2	10.2	-0,35

Thus, the PC of electricity spent for steam superheat cannot be compensated by increasing the internal efficiency of geothermal turbines and increasing enthalpy drop. However, when replacing wet steam turbine to the superheated steam turbine the efficiency of power plant at the values of α <0,015 can compensate the PC of electrolysis and increase the overall efficiency of power plants by 1-3% (Fig. 2). Taking into account the pressure increase of the turbine by reducing the hydraulic losses in the separator and by reducing the pressure in the condenser to the typical superheated steam turbines (4-5 kPa) the increase can account for 3-5%.

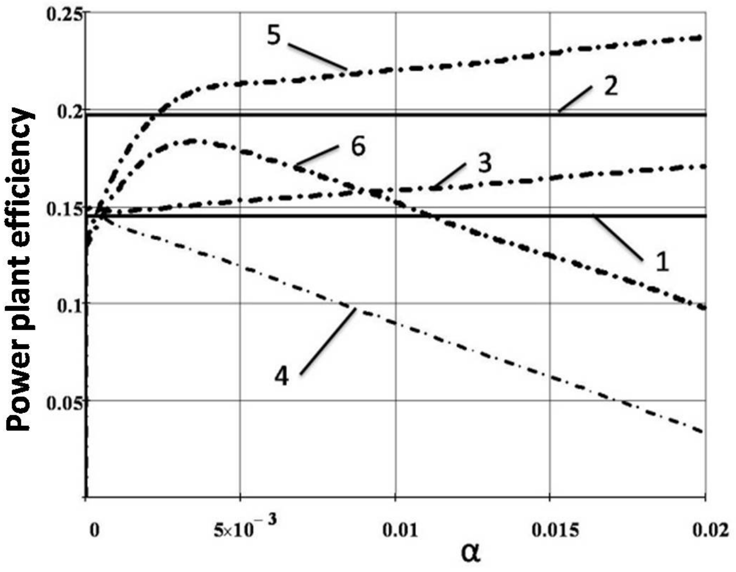

Figure 2: Changing the absolute efficiency of geothermal power plants, depending on α: 1 - GeoPP efficiency with wet steam turbine without superheating 2 - GeoPP efficiency with superheated steam turbine, 3 - GeoPP efficiency using superheating with wet steam turbine without the PC of electrolysis 4 - GeoPP efficiency using superheating with wet steam turbine including the PC of electrolysis, 5 - GeoPP efficiency using superheating without the PC of electrolysis and installing turbines at the superheated steam, 6 - GeoPP efficiency using superheating including the PC of electrolysis and installing turbines at the superheated steam.

4 Analysis of Electricity Cost Change with Hydrogen-Oxygen Superheating

At installing the hydrogen-oxygen steam superheating equipment a number of useful properties appear, which may reduce the annual costs of electricity, thereby reducing its price:

3. Reduction of steam humidity at the outlet of the turbine reduces the erosive tearing of the channel, which increases reliability and reduces the number of forced repairs;
4. an opportunity to balance load schedule, which allows power plant operation with a rated capacity of almost constant at optimum values of efficiency.

Annual production costs represent the amount of fuel costs, capital investment costs and operation expenses:

$$C = C_{fuel} + C_{cap} + C_{op} \tag{4}$$

The fuel component is taken equal to 0, because geothermal plant uses the heat of the Earth. The component of capital investment costs is determined by the following expression:

$$C_{cap} = P_a \cdot \Sigma S_{pp} + C_m = 1.2 \cdot P_a \cdot \Sigma S_{pp} \tag{5}$$

where P_a - depreciation rate, C_m - annual cost of maintenance, which we take as 20% of the depreciation, ΣS_{pp} - total cost of building a power plant.

Operating costs include the salaries of service personnel and other general station expenses and account for 55-65% of the depreciation. Unit cost of 1 kW of installed capacity (S_{pp}) is 900-1200 \$ / kW, and for additional equipment (S_{add}), where 95% of the cost is the cost of electrolyzers, this value is 1700-2200 \$ / kW. Let us assume the average value as $S_{add} = 2 \cdot S_{pp}$.

Denoting the relative power of installed additional equipment as θ, and the nominal power of power plant as N_{pp} [kW] we get the full cost of additional equipment:

$$\Sigma S_{add} = 2 \cdot \theta \cdot S_{pp} \cdot N_{pp} \tag{6}$$

The component of operating costs for the installation of additional equipment is practically unchanged, because its maintenance will require a slight increase in state employees. The cost of electricity generated is described by the following expression:

$$E_e = \frac{C}{N_{pp} \cdot 8760 \cdot K_r} \tag{7}$$

Finally, for calculating the cost of electricity, installation of additional equipment we get:

$$\frac{E'_e}{E_e} = \frac{(1.12 + 2 \cdot \theta + 0.6) \cdot 0.8}{(1.2 + 0.6) \cdot K'_r} = \frac{(1.72 + 2 \cdot \theta) \cdot 0.8}{1.8 \cdot K'_r} \tag{8}$$

where E'_e - the cost of electricity generated during the installation of additional equipment, K'_r - utilization coefficient of installed capacity, after the installation of additional equipment.

The results of calculation for different values of K'_r and θ are presented in Table 2.

Table 2

Θ	**K'_r**	**E'_e / E_e**
0.01	0.82	0.94
0.02	0.84	0.93
0.05	0.87	0.93
0.1	0.91	0.94
0.15	0.94	0.96
0.3	0.96	1.07

Thus, the optimal ratio of K'_r=0.85..0.90 and θ=0.03..0.07 lower cost electricity generated will be approximately 6-7%.

5 Conclusions

The use of equipment with hydrogen-oxygen superheat steam on geothermal power plants with wet steam turbines, increases the thermodynamic efficiency of workflow and increases the internal efficiency of the steam turbine, with its modernization, leading to increased efficiency of power plants by 4-6%. In addition, by improving equipment reliability, reduction of the cost of repairing and load management the total cost of electricity can be reduced by 6-7%. The results of the evaluations, optimum proportion of added high-temperature steam, which provides the greatest efficiency and lowest cost of installation of electricity produced, is in the range from 0.002 to 0.01.

References

[1] Shpilrain E.E, S.P. Malyshenko, G.G. Kuleshov: "Introduction in hydrogen energy", Energy atomic publishing house. Moscow, Russia, 1984.

[2] Malyshenko S.P., O.V. Nazarova, Y.A. Sarumov: "Some theymodynamic and perfomance aspects of hydrogen application in energy", Atomic-hydrogen energy and technology. v.8, p. 19, Energy atomic publishing house, Moscow, Russia, 1988.

[3] A.D. Truhniy., M.A. Izumov, O.A. Povarov,S.P. Malyshenko. “Foundations of modern power engineering”. ed.. A.D. Truhniy, Vol 1. Modern thermal power engineering /;MPEI publishing house, Moscow, Russia, 2008.

[4] T.H. Margulova “Nuclear power stations”. “High School”, Moscow, Russia, 1969.