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**THERMODYNAMIC ANALYSIS OF GEOTHERMAL
POWER SYSTEMS EMPLOYING SEPARATING EXPANDERS**

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MASTER

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Thermodynamic Analysis of Geothermal
Power Systems Employing Separating
Expanders

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1. Introduction

In a flash-steam geothermal power plant the production of the vapor is achieved through the simple, yet inefficient, process of throttling. Typical single-flash geothermal-steam cycles utilize only 40-45% of the work available in the geofluid at the wellhead whereas the more efficient dual-flash system utilizes only about 55% of the available work. These poor utilization efficiencies are attributed to the high entropy production associated with a throttling process. In this report we study the possibility of upgrading the thermodynamic performance of a direct-steam geothermal power plant through the use of a separating expander which produces work while achieving effective separation of the two phases. One such device is the Biphase rotary separator [1]. Preliminary testing of this device demonstrated that the isentropic efficiency is about 34% and that the separation efficiency is greater than 99.5% [1].

2. Preliminary considerations

In order to throw some light on the order of magnitude of the work loss in a throttling process we start by analyzing an ideal case. We assume that saturated liquid water is available at a wellhead temperature T_1 . The available work from this water is given by

$$w^o = h_i - h_o - T_o (s_i - s_o) \quad (1)$$

In this expression the subscript o designates a reference state determined by the ambient conditions and/or practical considerations. In this analysis we assumed a reference state corresponding to saturated liquid at 50°C. This choice was dictated by practical considerations rather than ambient conditions. A throttling process from T_i down to some arbitrary temperature T^* will result in a loss in the available work. The throttling process will thus result in degrading the available work from w^o to a value $w^* < w^o$. Figure 1 shows the dependence of both w^o and w^* on the initial temperature T_i when T^* is chosen as the arithmetic average of T_i and T_o . It can be seen that the throttling process has resulted in about 20% degradation of the available work regardless of the value of T_i .

Next we consider an ideal separator that separates the two-phase fluid resulting from the throttling (flashing) process into saturated vapor and saturated liquid both at T^* . The saturated liquid is rejected whereas the saturated vapor is expanded isentropically down to T_o in order to produce an amount of work w_s . The variation of w_s with T_i is shown in Fig. 1 together with the dryness fraction x^* of the fluid after the throttling process. It is noted that w_s amounts to less than 60% of the available work w^o . Naturally, in a real system the vapor expansion process will be an irreversible one and the actual amount of work produced will be much lower than the 60% quoted above. On the basis of a typical vapor expansion efficiency of 75% the single flash arrangement considered above will produce no more than 45% of the work originally available in the liquid. Nearly 35% of the loss is attributable to the throttling process; the remainder is due

[#] such as condenser design and handling of noncondensibles.

to the rejection of the separated liquid as well as the irreversibility in the vapor expansion process.

3. Analysis of a single-stage system

The arguments presented in the previous section indicate that a significant percentage of the available work is lost because of the entropy production in the flashing process. Part of this loss can be recuperated if the flash tank is replaced by a separating expander. A flow diagram of the system is provided in Fig. 2 together with its representation on a T,s chart. It is generally accepted [2] that a single-flash system will produce the maximum amount of work when T_i is chosen as the arithmetic average, T^* , of the initial temperature T_i and the condenser temperature T_o . When a separating expander is introduced between T_i and an arbitrary temperature T_1 , the optimum point will shift and the optimum value of T_1 will be lower than the arithmetic average T^* . The location of the maximum-work point will depend on the efficiency of the separating expander. Ideally, when the efficiency of the separating expander is 100% it is expected that the system will produce its maximum output when the expansion proceeds all the way from T_i to T_o . That is to say that T_1 will coincide with T_o in this case. Any value of $T_1 > T_o$ will result in a lower work output because of the loss of work in the rejected liquid combined with the irreversibility of the expansion process in the vapor turbine.

The equations governing the various processes in the systems are given below.

a) Process i-1; the separating expander

$$x_1^o = (s_i - s_1') / (s_1'' - s_1') \quad (2)$$

$$h_1^o = x_1^o (h_1'' - h_1') + h_1' \quad (3)$$

$$w_1 = \eta_1 (h_i - h_1^o) \quad (4)$$

where w_1 is the work developed by the separating expander which is assumed to have an efficiency η_1 . Substituting in eq. (4) we obtain

$$w_1 = \eta_1 [h_i - h'_1 - (s_i - s'_1) (h''_1 - h'_1) / (s''_1 - s'_1)] . \quad (5)$$

But

$$s''_1 - s'_1 = (h''_1 - h'_1) / T_1 . \quad (6)$$

then

$$w_1 = \eta_1 [h_i - h'_1 - (s_i - s'_1) T_1] . \quad (7)$$

Furthermore, the dryness fraction at the exit of the separating expander is

$$x_1 = (h_i - w_1 - h'_1) / (h''_1 - h'_1) , \quad (8)$$

or

$$x_1 = \left\{ h_i - h'_1 - \eta_1 [h_i - h'_1 - (s_i - s'_1) T_1] \right\} / (h''_1 - h'_1) . \quad (9)$$

This represents the amount of steam that will be expanded in the steam turbine between T_1 and T_o .

b) Process 1''-2; the steam turbine

$$x_2^o = (s''_1 - s'_2) / (s''_2 - s'_2) \quad (10)$$

$$h_2^o = x_2^o (h''_2 - h'_2) + h'_2 \quad (11)$$

$$w_s = x_1 \eta_s (h''_1 - h_2^o) , \quad (12)$$

in which η_s is the isentropic efficiency of the steam turbine and w_s is the work produced by this turbine per unit mass at point i. Substituting for h_2^o we obtain

$$w_s = x_1 \eta_s [h_1'' - h_2' - (s_1'' - s_2') T_2] , \quad (13)$$

in which we made use of the relationship

$$s_2'' - s_2' = (h_2'' - h_2')/T_2 , \quad (14)$$

with $T_2 = T_0$.

The above equations were utilized to compute both w_1 and w_s as a function of T_1 for three values of T_i (150, 200, 250°C). In all cases $T_0 = 50^\circ\text{C}$ and $\eta_s = 0.75$. The efficiency of the separating expander was varied from $\eta_1 = 0.0$ corresponding to the flash tank to $\eta_1 = 1.0$ corresponding to the ideal case. Between these two limits we considered two cases: first $\eta_1 = 0.3$ which represents the current state of affairs [1] and secondly $\eta_1 = 0.5$ which represents possible near-term improvements. The utilization efficiency is defined by

$$\eta_u = (w_1 + w_s)/w^0 , \quad (15)$$

where w^0 is given by eq. (1). The results are graphically depicted in Figs. 3, 4 and 5. Figure 6 illustrates the dependence of the optimum point (maximum η_u) on the expander efficiency.

4. Analysis of a two-stage system

The two-stage system is a variation on the dual-flash arrangement. Figure 7 contains a flow diagram of the system and the corresponding T, s diagram. It can be seen that the proposed two-stage system reduces to a conventional dual-flash arrangement if the two separating expanders I and II produce no work, i.e. if the efficiency of these expanders is zero. On the other hand, it is expected that the most efficient arrangement will result when the two expanders I and II operate at the best expected efficiency,

i.e. when $\eta_1 = \eta_2 = 0.5$ in our case. Between these two extremes, two important cases can be recognized:

- the first stage is a separating expander ($\eta_1 = 0.5$) whereas the second stage is a flash tank ($\eta_2 = 0.0$).
- the first stage is a flash tank ($\eta_1 = 0.0$) whereas the second stage is a separating expander ($\eta_2 = 0.5$).

We have analyzed these four cases for an initial temperature of 200°C. Our goal was to determine the optimum values of the intermediate temperatures T_1 and T_2 in each case. In all cases the steam turbine efficiency was taken as 0.75 and the condenser temperature was fixed at 50°C. Equations (2-14) of the previous section apply without modification to the analysis of the first stage. These equations have to be supplemented by the following equations for the second stage:

c) Process 1'-3; the second-stage expander

$$x_3^0 = (s_1' - s_2') / (s_2'' - s_2') \quad (16)$$

$$h_3^0 = x_3^0 (h_2'' - h_2') + h_2' \quad (17)$$

$$w_2 = (1 - x_1) \eta_2 (h_1' - h_3^0) \quad (18)$$

$$= (1 - x_1) \eta_2 [h_1' - h_2' - (s_1' - s_2') T_2] \quad (19)$$

The dryness fraction at point 3 is given by

$$x_3 = \left\{ h_1' - h_2' - \eta_2 [h_1' - h_2' - (s_1' - s_2') T_2] \right\} / (h_2'' - h_1') \quad (20)$$

d) Process 2, 2'-4; the mixing process

$$h_4 = [h_2'' x_3 (1 - x_1) + h_2 x_1] / [x_3 (1 - x_1) + x_1] \quad (21)$$

where

$$h_2 = h_1'' - \eta_s [h_1'' - h_2' - (s_1'' - s_2') T_2] \quad . \quad (22)$$

The dryness fraction at point 4 is obtained from

$$x_4 = (h_4 - h_2') / (h_2'' - h_2') \quad , \quad (23)$$

and the entropy at this point is given by

$$s_4 = s_2' + x_4 (s_2'' - s_2') \quad . \quad (24)$$

e) Process 4-5: the second steam turbine

$$x_5^o = (s_4 - s_5') / (s_5'' - s_5') \quad (25)$$

$$h_5^o = x_5^o (h_5'' - h_5') + h_5' \quad (26)$$

$$w_s' = \eta_s [x_1 + (1-x_1) x_3] (h_4 - h_5^o) \quad , \quad (27)$$

in which w_s' represents the work developed by the second steam turbine per unit mass at point i. Finally, the utilization efficiency, η_u in this case is given by

$$\eta_u = (w_1 + w_2 + w_s + w_s') / w^o \quad . \quad (28)$$

Figures 8, 9, 10, 11 display the results for the four cases considered. As would be expected the case of $\eta_1 = \eta_2 = 0.5$ yields the highest efficiency. The optimum efficiency for this system is about 67% as compared with an optimum value of only 53% for the dual-flash system. The figures also

demonstrate that there is no significant advantage in employing a flash tank in the first stage and a separating expander in the second over a single-stage system with a 50% efficient separating expander. Interchanging the flash tank and the expander, however, increases the optimum utilization efficiency from 59% to nearly 64%.

5. Conclusions

The analysis given in the previous sections indicates that separating expanders can provide a marked thermodynamic improvement over the flash tank arrangement. The analysis shows that even with relatively inefficient separators similar to the prototype tested by the Biphasic Company [1] an improvement of 18-21% is possible depending on the initial temperature of the liquid (the improvement is greater for low initial temperature). If the efficiency of the separating expanders can be upgraded from 30% to 50%, which may be achievable with further research and development, single stage systems can produce from 35% ($T_i = 250^\circ\text{C}$) to 52% ($T_i = 150^\circ\text{C}$) more work than the equivalent single-flash systems. On the other hand, with the same level of expander efficiency, the two-stage system reflects a 26% advantage over the equivalent dual-flash system. It should be noted, however, that the optimum intermediate temperatures exhibit a pronounced dependence on the efficiency of the expanders.

We also note that the Biphasic device is not the only one that can achieve separation of the phases while producing work. The same functions may be performed by a combination of a total flow expander [3, 4] and a conventional separator.

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Captions to Figures

- Fig. 1. Available and lost work in a single flash system
- - - x^* , dryness fraction after flashing
- Fig. 2. A single stage system with a separating expander and its representation on the T-s diagram.
- Fig. 3. Utilization efficiency, η_u , for single-stage systems, $T_i = 150^\circ\text{C}$.
- Fig. 4. Utilization efficiency, η_u , for single-stage systems, $T_i = 200^\circ\text{C}$.
- Fig. 5. Utilization efficiency, η_u , for single-stage systems, $T_i = 250^\circ\text{C}$.
- Fig. 6. Optimum operating conditions for single-stage systems.
- Fig. 7. A two-stage system with separating expanders and its representation on the T-s diagram.
- Fig. 8. Utilization efficiency for a two-stage system, $\eta_1 = \eta_2 = 0.0$ (the dual-flash system).
- Fig. 9. Utilization efficiency for a two-stage system, $\eta_1 = 0.5$, $\eta_2 = 0.0$.
- Fig. 10. Utilization efficiency for a two-stage system, $\eta_1 = 0.0$, $\eta_2 = 0.5$.
- Fig. 11. Utilization efficiency for a two-stage system, $\eta_1 = \eta_2 = 0.5$.

Figure 1

SE : separator expander
ST : steam turbine

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 3

Figure 3

Figure 10

Figure 11