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HYBRID STAGING OF GEOTHERMAL ENERGY CONVERSION PROCESSES

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ABSTRACT

A hybrid system consists of two or more energy conversion processes. This study examines the use of three energy conversion machines in hybrid systems: the conventional single-phase turbine, and the two-phase expanders known as the Lysholm engine and the radial outflow reaction turbine. Two hybrid systems are presented. The first is a two-stage, single-flash system with the Lysholm engine as the first stage, and a separator and conventional turbine as the second stage. The second system adds a radial outflow reaction turbine to recover a part of the energy rejected in the second stage. A theoretical specific power of 41.3 kW•s/lb is predicted for the two-stage, single-flash hybrid system. The addition of the radial outflow rotary turbine increases performance to 44.8 kW•s/lb. Both are superior to the double-flash system, with a specific power of 37.8 kW•s/lb. In addition, the hybrid system offers operating flexibility.

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INTRODUCTION

Geothermal reservoirs such as those in the Imperial Valley, California, contain a mixture of liquid and vapor. In the Imperial Valley, the mixture quality (dry steam fraction) at the wellhead ranges to 40%, and reservoir temperatures range from 300°F (149°C), which is about the lowest feasible temperature for geothermal electric power generation, to 450°F (382°C), which is about the highest reservoir temperature found in the U.S. Pressure can be as high as 400 psia (2.75 MPa), and dissolved minerals can account for as much as 30 wt% of the geothermal fluid. Because of the variety of thermodynamic states and chemistries in the geothermal resources of the Imperial Valley, no one energy conversion machine or process can satisfy all conditions. This is one reason why so many energy conversion processes are being studied. Staging, and particularly the staging of dissimilar energy conversion machines, is a method of increasing the efficiency of the energy conversion process.

A hybrid system consists of two or more energy conversion processes. Several investigators have proposed hybrid systems at different times and for various applications, and many such systems are possible because there are many energy conversion machines. However, only three conversion machines have proven potential, meaning that they have been operated under real or simulated geothermal conditions. These are the conventional single-phase (dry steam) turbines and the two-phase expanders known as the Lysholm engine and the rotary outflow reaction turbine. These last two conversion machines have proven capable of generating geothermal power with the state of technology as it is. This report describes how two-phase expanders and single-phase turbines can be combined by staging in simple hybrid systems.

CONVENTIONAL TURBINES

The term conventional turbine seems all-encompassing, but it is really an abbreviated description of the conventional low-pressure condensing turbine used in all fossil-fired or nuclear-fired power plants. These are characteristically reaction-bladed, low-pressure turbines, and consequently they are required to handle large flow volumes of wet steam (0 to 10% wetness). Low-pressure reaction turbines have engine efficiencies ranging up to $\eta_e = 0.85$ for the largest turbines, with saturated steam as a working fluid. The engine efficiency for a 1-MW turbine would be approximately $\eta_e = 0.75$, and it would be even lower for smaller sizes. We have chosen an engine of $\eta_e = 0.7$ for later calculations.

Low-pressure reaction turbines are highly developed and have been much studied. They have problems such as blade structure (including length and height), tip speed, corrosion, erosion, and handling of moisture, but these turbines are used widely. Experience with low-pressure reaction turbines is extensive. They are the most expensive elements of any steam power plant and they are also the size-limiting unit for any combined system. That is, the last state of the low-pressure turbine is the feature that limits the volume flow of the combined system.

LYSHOLM ENGINE

The Lysholm engine, or helical expander, consists of two, side-by-side meshing helical rotors (Fig. 1). It is a positive-displacement machine that takes in a discrete volume of fluid which then expands against the rotors, doing work. Physical contact between the rotors is prevented by a set of timing gears. The absence of internal wearing parts, the inherent mechanical balance, and the ability to operate at high rotary speeds are all attractive features of the Lysholm design. The rotors are basically rugged and their meshing action tends to keep them clean by continuous scraping that removes scale, although this process has not actually been demonstrated.

FIG. 1. How the Lysholm engine works.

The original development of the Lysholm design dates back over 40 years to when A. Lysholm designed and built the first practical helical-lobe compressor. At that time, he was Chief Engineer of A. B. Ljungstroms Angturbin, which was the earlier name of Svenska Rotor Maskiner. His work is well-documented by numerous patents² and by his paper³ published in 1943 by the Institution of Mechanical Engineers. In 1952, H. R. Nilsson patented a helical rotary engine.⁴ In 1966, Lysholm described the application of the design as a screw engine.⁵ In 1973, R. Sprankle patented the use of the Lysholm engine for a geothermal application where water is the main geothermal fluid.⁶ The basic concept of the Lysholm engine for such applications has been demonstrated in field tests of a modified air compressor unit with 6-in.-diam rotors by R. Sprankle of the Hydrothermal Power Company, Ltd.⁷ At the Lawrence Livermore Laboratory, the Lysholm engine has been studied extensively for high-temperature users and as a topping engine for Rankine cycles. Wells et al.^{8,9} first recognized the rugged characteristics of the engine for use in severe environments.

Another unit specifically built as a geothermal engine was tested extensively at Lawrence Livermore Laboratory. Results indicate that the Lysholm engine can operate well with a two-phase mixture as a working fluid. The maximum observed engine efficiency was 53% at 8000 rpm, with an inlet pressure of 190.6 psia, 22.2% quality, and an exhaust pressure of 30.6 psia. The best results were observed at the higher speeds and with exhaust to an above-atmospheric back pressure.¹⁰ Other results show that speeds to 15,000 rpm¹¹ and engine efficiencies up to $\eta_e = 0.8$ are possible. Figure 2 shows typical performance characteristics of the Lysholm engine at 7500 rpm and 30.6 psia back pressure.

The most obvious geothermal application of the Lysholm engine is as the upper stage of a two-stage hybrid system. From our data, more than a reasonable value of engine efficiency for the Lysholm engine expanding to more than atmospheric pressure is $\eta_e = 0.6$. This is the value used in later calculations.

FIG. 2. Typical performance characteristics of the Lysholm engine.

Conventional steam turbines are well-developed and have excellent performance if given good steam conditions. The steam turbine is most efficient with dry steam at inlet and limited moisture in the exhaust. Geothermal fluids generally have a great deal of moisture and must be used as a two-phase mixture or as separated phases. There are effective energy conversion machines that use a two-phase mixture or a liquid. The systems described below are a few of the more attractive combinations or hybrids with steam turbines and other expanders.

RADIAL OUTFLOW REACTION TURBINE (RORT)

The radial outflow reaction turbine (RORT) is a modern adaptation of two very early reaction turbines, Hero's turbine and Barker's mill. Hero's reaction turbine was essentially a saturated vapor turbine. Saturated vapor was fed to ducts leading to revolving vapor nozzles. The device employed in Barker's mill was used to produce mechanical power from a stream or river elevation change. It consisted of a hydraulic reaction turbine where power was developed by revolving liquid nozzles.

In the RORT, hot water is conducted radially outward within a rotating turbine disk to rotating nozzles located on the periphery. The hot water flashes to vapor as the fluid moves through the two-phase nozzles, producing thrust. Figure 3 is a drawing of the radial outflow reaction turbine. This form of the reaction turbine is distinct from its predecessors because of two-phase expansion in the revolving nozzles. Lawrence Livermore Laboratory has built and tested a 16-in.-diam, radial-outflow reaction turbine. Experimental measurements^{12,13} yield an engine efficiency between $\eta_e = 0.3$ and 0.4 . For purposes of later calculations, we chose an engine efficiency of $\eta_e = 0.4$. Figure 4 shows typical performance characteristics.

FIG. 3. How the radial outflow turbine works.

FIG. 4. Typical performance characteristics of the radial outflow rotary turbine.

BASIC ASSUMPTIONS

To compare hybrid and conventional flash systems, we made the basic following assumptions:

- We assumed an engine efficiency of $\eta_e = 0.4$ for all radial outflow reaction turbines, an engine efficiency of $\eta_e = 0.6$ for all Lysholm engines, and an engine efficiency of $\eta_e = 0.7$ for conventional turbines. As previously stated, these efficiencies are all considered to be the state of current practice.
- We assumed a set of arbitrary wellhead conditions. Geothermal conditions within such an extensive resource as the five areas in the Imperial Valley classified as "known geothermal resource areas" (KGRA) are quite varied. As stated, vapor quality varies from 0 to 40% and vapor temperature may range from 300 to 450°F (150 to 232°C). Any well and any wellhead condition could have been accepted, but the data we used were that of Imperial Irrigation District Well No. 1.¹⁴ For this well, the enthalpy was measured at 422.8 Btu/lb, (235 cal/g). Figure 5 shows the flowing characteristics of this well. Because the sole purpose of this assumption is to make direct comparisons between systems, the wellhead conditions were not varied.

FIG. 5. Well characteristics.

The theoretical power available from isentropic expansion of the well head fluid, given the stated conditions, is

$$\text{theoretical available power} = \frac{3600W(h_2 - h_{3s})}{3.413 \times 10^6} .$$

The actual power is somewhat less because the vapor expansion is not isentropic:

$$\text{actual power} = \frac{3600W(h_2 - h_3)}{3.413 \times 10^6} .$$

As a measure of performance, each stage analyzed had an overall engine efficiency of η_e , defined by the ratio

$$\eta_e = \frac{\text{actual power}}{\text{theoretical power}} = \frac{h_2 - h_3}{h_2 - h_{3s}} .$$

In the case of multiple-staged systems, the power produced in each stage is computed separately. The total power for the system is the sum of the power from all the stages.

Figures 6(a through d) show the thermodynamic processes from the geothermal wellhead to the reinjection well for several hybrid systems. Figure 6(a) is a single-stage system with no vapor-liquid separation. Figure 6(b) is the standard single-stage, single-flash system, and Fig. 6(c) is the two-stage double-flash system. All have a wellhead pressure of 150 psia, an exhaust pressure of 1.8 psia, and no losses. Figure 6(d) is the two-stage, single-flash hybrid system.

FIG. 6. (a) Single-stage system, (b) single-stage, single-flash system, (c) two-stage, double-flash system, (d) two-stage, single-flash system.

FLASH STEAM PROCESSES

The most commonly used conversion process for power generation from a liquid-dominated geothermal well is the flash steam process. Figures 6(a and b) show single-stage flash steam processes. The well flow leaves the wellhead at a pressure below the reservoir pressure, during which time a part of the flow flashes to vapor. The flow is usually throttled. The mixture of liquid and vapor enters a separator from which the liquid flows to the reinjection well and the saturated steam flows to a conventional turbine for power generation where it is condensed at subatmospheric pressure. The condensate is pumped from below atmospheric pressure to above atmospheric pressure and is then either reinjected or directed to a cooling tower.

In Fig. 7(a), the flash steam system is not optimized. A turbine inlet pressure of 150 psia is used primarily for later comparisons; it is 10 atm, the lowest pressure for which flow measurements at well No. 1 IID were made by Helgeson.¹⁴ Between each component are the state conditions and flow rates of the vapor-liquid mixture. The temperature is listed first, in degrees Fahrenheit, the pressure P is listed second, in lb/in.² absolute, the enthalpy H is listed third, in Btu/lbm. The flow rate $\dot{W}$ is listed last. The units are normalized to 1-lb flow--or 1 lb/s flow rate--at inlet and exit. There are no pressure drops or other losses in piping or controls. This study is simply for a comparison of overall cycle efficiencies and component size. The engine efficiency indicates overall performance and the normalized flow rate indicates component size.

As the separator inlet pressure is reduced, the mass flow of steam to the turbine increases and the available energy decreases. The optimum separation pressure is a balance between these two. Figure 7(b) shows the optimum separation pressure of 48 psia, which, for the assumed wellhead conditions,

FIG. 7. Flash steam process; (a) not optimized, (b) with optimum separation pressure.

FIG. 7. Continued.

is quite low. This is typical, but note that most wells are not allowed to flow at such wide-open conditions. At Wairakei in New Zealand, which has both double-flash and triple-flash systems, the first-stage flash separation is low, 65 psia.¹⁵

Figure 8 shows the variation of specific power output with separator pressure. The separator may be either of two conventional types, the cyclone separator or the horizontal separator. With high brine concentration, the steam line to the turbine may include scrubbers to remove entrained salts. The condenser is usually a barometric or direct condensor where water from the cooling tower is sprayed directly into the condensing steam. Noncondensable gases in the steam must be pumped from the condenser to the atmosphere by mechanical pumps or by steam jet ejectors.

FIG. 8. Specific energy of a single-stage, single-flash system as a function of separator pressure.

MULTIPLE-FLASH SYSTEMS

A multiple-flash system can be used as an alternative to the single-flash system. Saturated water from the first separation is flashed to a mixture of steam and water at a lower pressure in a second separation. The internal energy of the saturated liquid is partially recovered as saturated vapor at a lower pressure, but the internal energy of the liquid in the second separation is not recovered. A third, fourth, and fifth separation could be used, but with increasing cost and diminishing return.

A two-stage, double-flash system is shown in Fig. 9. The liquid from the first separator is directed to a second separator. Before reaching the second separator, it is throttled a second time, reducing its pressure to that of the steam and liquid leaving the first-stage steam turbine. The two streams are combined and the resulting liquid and vapor mixture is separated in the second separator. The steam from the second separator flows to the second-stage turbine, and the liquid flows to the reinjection well. The exhaust steam from the second-stage turbine is then condensed and either reinjected or directed to cooling tower.

In theory, in a multistaged system, equal enthalpy drops between stages split the total engine work into approximately equal segments. That each stage has the same engine efficiency is a criterion for optimum performance in staged fluid machines. If the stage efficiencies are different, several iterations of a heat balance are required to find the optimum division. In the two-stage flash system in Fig. 9, no attempt was made to complete this iteration. For the given conditions, the optimum second separator pressure would be approximately 16.5 psia. Unfortunately, blowdown, which is necessary to rid the separator of solids, requires a higher pressure. The pressure selected for the second separation was somewhat arbitrarily taken as 25 psia. There

FIG. 9. Two-stage, double-flash system.

would be a difference, albeit a small one, between engine efficiencies for the combined cycles using an arbitrary separation pressure of 25 psia and an optimum separation pressure, but the higher pressure would be more practical.

TWO HYBRID SYSTEMS

The first hybrid system considered is a two-stage, single-flash system. The Lysholm engine, which can operate with a two-phase working fluid, replaces the first-stage separator and first-stage conventional turbine. A second-stage separator, a conventional turbine, a condenser, and a condensate pump complete the system [see Fig. 10(a)].

With the Lysholm engine, the overall cycle efficiency is 0.555 and the specific power is 42 kW/lb, nearly 10% higher than a comparable two-stage, double-flash system, and with fewer pieces of equipment.

The second hybrid system has an additional radial outflow reaction turbine to recover a part of the energy lost in the liquid rejected from the separator [Fig. 10(b)]. Although the engine efficiency of the RORT is low, no other energy conversion machine can accept liquid as a working fluid. The energy recovered increases the total energy of the system to 45.7 kW/lb, another 10% over the first hybrid system, and 19% over the two-stage, double-flash system shown in Fig. 9.

The increased efficiency of hybrid systems, which include two-phase energy conversion machines as well as conventional turbines, can be stated still more dramatically if we consider a three-stage, triple-flash system. Such a system is shown in Fig. 11, and has been optimized. It is technically feasible, but the economic feasibility is borderline. Wairakei has three stages for some of its high-pressure bores, but it is the only existing or planned three-stage system. The important point is that the two-stage, single-flash hybrid system, with or without the RORT, performs better than an optimized three-stage, triple-flash system.

FIG. 10. (a) Two-stage, single-flash system, (b) with RORT added.

FIG. 10. Continued.

FIG. 11. Three-stage, triple-flash system.

CONCLUSIONS

Two conclusions can be drawn from these performance data:

- The two-stage, single-flash hybrid system consisting of a Lysholm engine, an interstage separator, and a conventional turbine, in theory, will perform better than a comparable two-stage, double-flash system.
- A radial outflow reaction turbine used to recover part of the energy lost in the liquid rejected from the separator further increases the performance over the two-stage, double-flash system.

These predicted performance data for hybrid systems, coupled with their inherent simplicity, are sufficient causes to seek further and more detailed study of staged hybrid systems.

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