ADVANTAGES OF USING MIXTURES AS WORKING FLUIDS IN GEOTHERMAL BINARY CYCLES

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Advantages of the use of mixtures compared to pure fluids as working fluids in geothermal binary cycles are discussed with attention to effective use of the geothermal resource and cost effectiveness, not merely thermal efficiency. Calculations are presented to support the argument that mixtures can be tailored to effectively match the characteristics of the resource geothermal fluid better than virtually any pure fluid choice for the working fluid.

The United States government is currently sponsoring a large research program in geothermal power generation, including major projects involving binary cycles. However, to date, little effort has been put into optimally choosing working fluid mixtures and operating conditions for geothermal binary cycles. In a recent proposal, "Resource Utilization Efficiency Improvement of Geothermal Binary Cycles - Phase I", (K. E. Starling, principal investigator) submitted to the Energy Research and Development Administration by the University of Oklahoma in February, 1975, the use of mixtures rather than pure fluids as working fluids in geothermal binary cycles is recommended. The major objective of the present paper is to elucidate some of the advantages of mixtures over pure fluids as working fluids in geothermal binary cycles.

The Geothermal Binary Cycle

By definition, in a geothermal binary cycle, the working fluid in the power production cycle (*e.g.* Rankine-type cycle) receives energy by heat transfer with the geothermal fluid. In the typical geothermal binary cycle, the geothermal fluid from a production well is used in heat exchange to increase the temperature of the pure working fluid in the high-pressure liquid phase from near the lowest temperature in the cycle to the highest temperature in the cycle, where the working fluid is a gas. The geothermal fluid may then be utilized further or returned to the geothermal reservoir via a reinjection well as shown in Figure 1. The high-pressure, high-temperature working fluid (gas phase) is then expanded through a turbine for power generation. Commonly, the turbine drives a generator to produce electric power. After expansion, the pure working fluid is near the lowest pressure in the cycle and usually is a superheated vapor, generally at a temperature above its dew point temperature. The low-pressure vapor is then cooled and condensed to liquid at nearly constant pressure by heat exchange with cooling water. The working fluid, which is now in the liquid state at the lowest temperature and pressure in the cycle, is then compressed to the highest pressure (for heat exchange with the geothermal fluid), thus completing the cycle undergone by the working fluid.

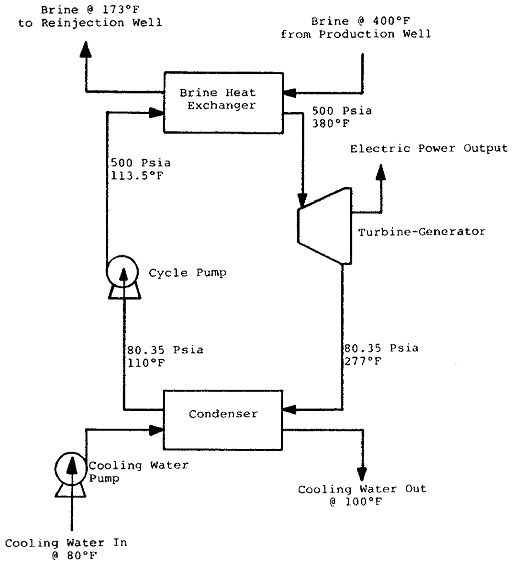

FIGURE 1. Typical isobutane geothermal binary cycle.

Pure Working Fluids

The temperatures and pressures shown on

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the schematic diagram of the geothermal binary cycle in Figure 1 are for the case of a geothermal brine at 400 F, cooling water at 80 F, and use of isobutane as the working fluid in essentially the process proposed by Anderson (1). Calculations were made for this binary cycle using turbine and pump efficiencies of 85% (based on adiabatic reversible expansion and compression), adiabatic operation of heat exchangers capable of 500 psia pressure and a 20 F rise in the cooling water temperature and a 10 F minimum approach temperature. In addition, the pressure drop of the working fluid in the heat exchangers and the pumping requirements for brine reinjection were ignored. For these conditions, the cycle undergone by the isobutane is shown in Figure 2 on a temperature-entropy diagram. The calculations were made using self-consistent thermodynamic data for isobutane (2), with the numerical results shown in Table 1.

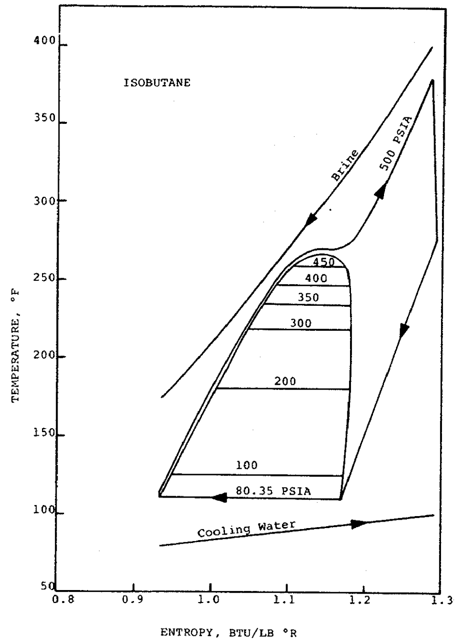

FIGURE 2. Temperature — entropy diagram for isobutane cycle.

Conceivable methods for improving the pure-fluid geothermal binary cycle include the following schemes (for a plant of specified net power output). (a) Higher pressures can be used in the cycle, which increases the net cycle thermal efficiency (net energy output divided by energy input from geothermal fluid) and decreases geothermal fluid and cooling water requirements, but generally increases plant capital costs and operating problems. (b) Preheating of the high-pressure condensed working fluid with the low-pressure vapor-phase working fluid leaving the turbine can be used, thereby increasing cycle thermal efficiency and decreasing cooling water requirements but often yielding greater capital costs and virtually no more energy output per unit mass of resource geothermal fluid. (c) A higher-molecular-weight pure working fluid, such as isopentane, can be used, thereby yielding less superheat both at the turbine entrance and exit, while producing virtually no more energy output per unit mass of geothermal fluid. In fact, for hydro-

TABLE 1. ***Comparison of isobutane and mixture geothermal binary cycles***

	Working fluid	
	Isobutane	Mixture[a]
Brine inlet temp. (F)	400.0	400.0
Brine outlet temp. (F)	172.9	196.1
Cooling water inlet temp. (F)	80.0	80.0
Cooling water outlet temp. (F)	100.0	100.0
Cooling water reqd. (lb. per lb. brine)	9.95	8.69
Turbine inlet temp. (F)	380.0	380.0
Turbine inlet press. (psia)	500.0	500.0
Turbine outlet temp. (F)	277.0	247.9
Turbine outlet press. (psia)	80.35	40.48
Turbine outlet liquid (vol. %)	0.0	0.0
Pump inlet temp. (F)	109.8	90.0
Pump outlet temp. (F)	113.5	93.2
Net work[b] (BTU per lb. brine)	30.38	32.24
Cycle net thermal efficiency (%)	13.2	15.7
Evaporator LMTD (F)	24.1	25.3
Condenser LMTD (F)	31.3	17.11

[a] Mixture composition, in mole percent: 56% isobutane, 44% isopentane.
[b] Turbine and pump efficiencies of 85%, based on adiabatic reversible expansion and compression, used in calculations.

carbons of molecular weight larger than butane, the additional problem of retrograde condensation and vaporization within the turbine may be encountered, which may lead to major turbine design problems. The trade-offs within the framework of the various designs options for pure fluids vary with the temperature of the resource geothermal fluid and a detailed study of these trade-offs is beyond the scope of this paper. However, the following points should be emphasized. Because the spectrum of resource geothermal fluid temperatures for economically feasible geothermal binary cycles using organic fluids ranges continuously from about 300 F up to 700 F, while pure fluid behavior changes discretely from fluid to fluid, it may be virtually impossible to match a pure working fluid to the resource. On the other hand, an essentially infinite spectrum of property behavior characteristics exists for mixtures and thus a mixture can in principle be found which matches the resource characteristics better than virtually any possible pure-fluid choice.

Use of Mixtures as Working Fluids

The advantages of using mixtures rather than pure compounds as working fluids in geothermal binary cycles can be explained in part with reference to the differences in pure fluids and mixture cycle design calculations summarized in Table 1 and cycle temperature-entropy diagrams, shown in Figures 2 and 3. The pure fluid cycle in Figure 2 is for isobutane, while the mixture cycle in Figure 3 is for a two-component mixture. The composition of this mixture is 56% isobutane and 44% isopentane, on a mole percentage basis. The temperature-pressure conditions for Table 1 and Figures 2 and 3 are for the case of a geothermal fluid at 400 F and cooling water at 80 F, with expansion of the working fluid from 500 psia to 80.4 and 40.5 psia, respectively. The turbine exit pressure of 80.4 psia is chosen for the isobutane cycle to insure complete condensation in the condenser at 110 F, thereby allowing a 10 F minimum approach temperature. The choice of 40.5 psia for the turbine outlet pressure results in a mixture condensing curve which is very nearly parallel to that of the cooling water, a situation which should minimize irreversibilities in the condenser. A disadvantageous result is that the effective log mean temperature difference (LMTD) for the mixture is only about 55% of that for the isobutane cycle. Hence, the mixture condenser would probably be larger than the isobutane condenser. The trade-off would have to be determined by optimization of the cycles based on equipment sizing and economics which is beyond the scope of this paper.

In Figures 2 and 3 the difference between the areas under the cycle heating and cooling curves for the working fluid represents the work obtained from the cycle per pound of geothermal fluid (before accounting for work required for pumping cooling water or geothermal fluid). The geothermal fluid is considered to have the properties of supercooled liquid water. Pertinent information from the calculations for both the isobutane and mixture cycles is summarized in Table 1. Predictions of enthalpies, entropies, densities, dew points, bubble points, and vapor-liquid equilibria for the working fluids were made using accurate correlation (2). Although the composition of the mixture used for this comparison is not optimized with respect to its warming curve at 500 psia, the composition chosen does offer distinct advantages over pure isobutane in a number of respects. The fact that the mixture and the isobutane leave the turbine with 138 F and 167 F super-

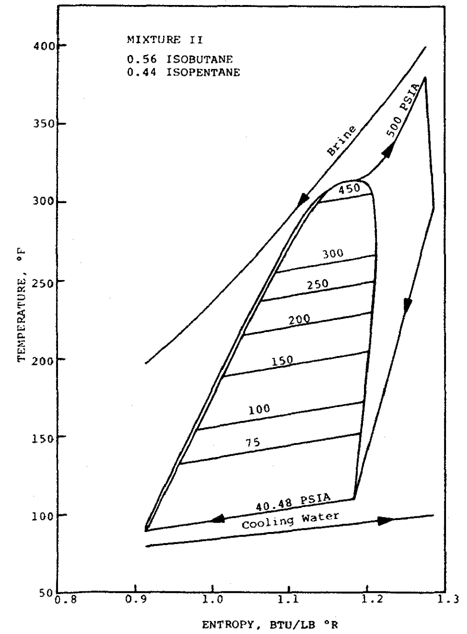

FIGURE 3. Temperature — entropy diagram for mixture cycle.

heat, respectively, means that expansion from a higher inlet pressure would lead to greater turbine work yield per pound of geothermal fluid, corresponding roughly to the triangular-shaped areas below the cooling curves for the mixture and isobutane from the turbine exit to the respective dew points at 110 F. The condenser duty is greater and 14.5% more cooling water is required for the isobutane cycle than for the mixture cycle. The bubble-point temperature of the mixture at 500 psia is rather high, 300 F. To maintain a temperature difference between the geothermal fluid and the working fluid mixture of at least 10 F throughout the heat exchanger, the exit temperature required for the geothermal fluid is 196 F compared with 173 F for the isobutane cycle. Nevertheless, more work is obtained per pound of geothermal fluid in the mixture cycle than the isobutane cycle, because the thermal efficiency of the mixture cycle is 15.7% compared to 13.2% for the isobutane cycle. Because the geothermal fluid leaves the heat exchanger at 196 F in the mixture cycle, it could be used in heat exchange with a second working fluid mixture to obtain additional work. Thus, a cascade system of two or more binary cycles could be developed to increase the work obtainable per pound of geothermal fluid passing through the geothermal power plant.

CONCLUSIONS

The preliminary calculations for even the unoptimized mixture considered here demonstrate potential advantages in using mixtures as working fluids in binary cycles to increase turbine work and decrease condenser duty and cooling water requirements, and the potential for cascade systems of binary cycles in which the work obtained from the coupled cycles is maximized.

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