Geothermal Resources Council *Transactions*, Vol. 22, September 20-23, 1998

Flowsheet Simulation of the Trilateral Cycle

Blaine W. Brown and Gregory L. Mines
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625, Idaho Falls, ID 83415-3635

ABSTRACT

The trilateral cycle has been identified as a potential performance advantage over a conventional binary cycle for energy recovery from low-temperature resources. This paper details calculations to assess the applicability of 20 different working fluids in the trilateral cycle for energy recovery from geothermal brines over a temperature range of 200 to 320°F. Differences in net power of approximately 50% were calculated for the various fluids at the lowest temperature considered; at the highest temperatures the differences in net power were less pronounced. The selection of a working fluid for the trilateral cycle is dependent upon the resource temperature and any limitation on the expansion ratio of the fluid through the expander; some types of expanders may be limited to operation with lower expansion ratios. The more volatile of the fluids evaluated had the lower expansion ratios; these fluid included propane, Refrigerant 134a, ammonia, Refrigerant 40, isobutane, and n-butane.

The simplicity of the trilateral cycle may make it competitive with the binary cycle for energy recovery from low temperature heat sources, especially if two-phase expanders can be developed that have high efficiencies. Calculations suggest that the trilateral cycle can utilize a given geothermal resource more efficiently than can a conventional binary cycle. Relative to a binary cycle operating with an 85% expander efficiency, the trilateral cycle would have a performance advantage provided the two-phase expander had an isentropic efficiency of about 76% or more. One advantage of the trilateral cycle is the potential for a lower operating pressure compared to the binary cycle evaluated. This should result in lower costs for components of equivalent size.

Introduction

The trilateral cycle is a thermodynamic cycle that may be particularly well-suited for energy recovery for low to moderate temperature energy sources. The cycle consists of isentropic pumping of a working fluid, isobaric heating of the working fluid to the bubble point, isentropic expansion of the working fluid producing a two-phase mixture, and isobaric condensation of the two-phase mixture. The primary difference between the trilateral cycle and the conventional binary cycle is that, in the trilateral cycle, the working fluid remains a liquid as it leaves the heater, and the fluid expansion through the expander occurs entirely within the two-phase region. The key to practically implementing the trilateral cycle is the expansion of the pressurized liquid into the two-phase region; typically turbines are not designed to operate with two phases. Because the heating curve of the working fluid is closely matched to the cooling curve of the brine, the associated irreversibilities are greatly reduced and the first law efficiency of the trilateral cycle is higher than that of a conventional geothermal binary cycle. Therefore, the trilateral cycle may be able to recover more energy than a conventional binary cycle from a low temperature source.

Approach

Calculations were made over a temperature range of approximately 200 to 320°F, with the trilateral cycle process conditions being optimized to produce a maximum net power output for a number of different working fluids. For a given resource temperature, the optimized trilateral cycle was compared to the performance of a conventional binary cycle to establish the conditions producing a performance advantage.

Cycle Model

The trilateral cycle and the binary cycle are shown on temperature-entropy diagrams in Figures 1 and 2, respectively. The trilateral cycle (isentropic pumping, isobaric heating to the bubble point, isentropic expansion into the two-phase region, and isobaric condensation) is contrasted with the conventional

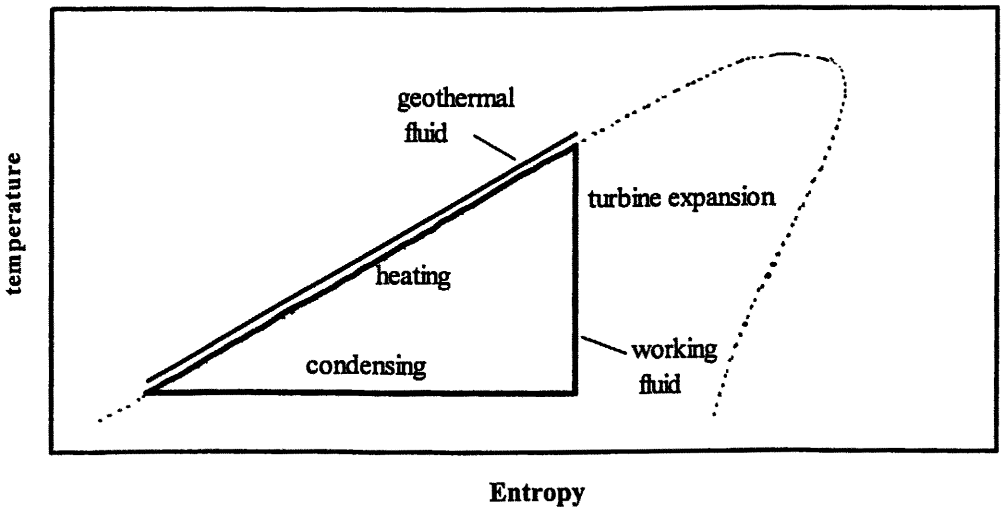

Figure 1. Temperature-Entropy Diagram for Trialteral Cycle.

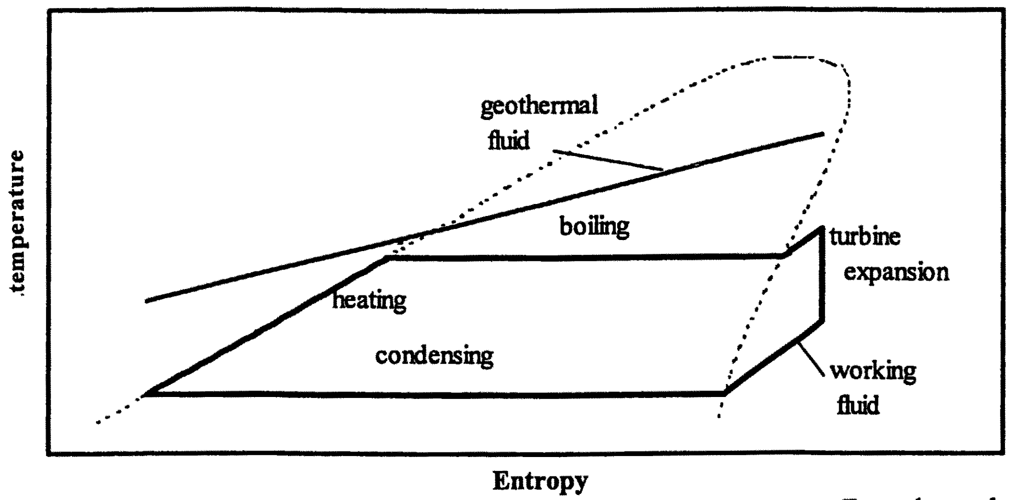

Figure 2. Temperature-Entropy Diagran for Binary Cycle.

binary cycle (isentropic pumping, isobaric heating into the superheated region, isentropic expansion within the superheated region, and isobaric condensation). Calculations were made for both cycles using ASPEN PLUS to model each system's performance. ASPEN PLUS is a chemical process simulator that calculates mass and energy balances from user-defined process flow diagrams. The code can model unit operations such as pumps, turbines, and heat exchangers, as well as detailed feedback loops and design specifications.

Assumptions

Certain assumptions are common to modeling both the trilateral cycle and the binary cycle. These include the following:

- 450 gpm brine flow rate (flow rate anticipated for a remote, off-grid applications).
- Pump isentropic efficiency of 85% with pump motor efficiency of 98 %.
- Expander isentropic efficiency of 85%.
- Pressure drop of 10 psi between the pump and the heater to account for frictional losses, control valves, etc.
- Working fluid pressure drop of 25 psi in heater.
- Expander mechanical efficiency of 96% (includes 98% generator efficiency).
- Air-cooled condenser.
- Condenser tube side (working fluid) pressure drop of 1 psi.
- Fan power requirement of 1 HP per 9000 cfm of air flow.
- Cooling air inlet temperature of 60°F.
- Condensing temperature of 100°F.
- Heater and condenser approach temperatures are each set to 10°F.
- Cooling air mass flow rate is varied to allow 10°F approach temperature in the condenser.

The ASPEN PLUS flowsheet model for the trilateral cycle included the following assumptions:

- Pump outlet pressure is allowed to vary such that the pressure at the expander inlet is 1 psi greater than the bubble point. This ensures that the working fluid is liquid at the expander inlet.
- Pump outlet pressure does not exceed the critical pressure.

- Approach temperature in heater is specified to be 10°F by varying heater outlet temperature (working fluid).
- Working fluid mass flow rate is varied to allow maximum net power from the cycle for each working fluid, subject to all other conditions and constraints.

The ASPEN PLUS flowsheet model for the binary cycle included the following assumptions:

- The working fluid leaving the brine heat exchanger is completely vaporized.
- Maximum net power for each working fluid is determined by varying the pump outlet pressure, the working fluid mass flow rate, and the heater outlet temperature, subject to all other conditions and constraints.

Similar convergence methods could have been used for both cycles; however, it was found that slightly different schemes led to faster convergence.

Temperature Limits

The trilateral cycle has a potential performance advantage over a conventional binary cycle because of the reduced irreversibilities in the heat addition portion of the cycle. In an ideal trilateral cycle, the specific heats of both fluids remain constant during this heat exchange process, resulting in a constant approach temperature throughout the heat exchange process. The heat addition process in an actual cycle will approach this idealized process as long as the specific heats remain approximately constant and there are no temperature restrictions placed on either fluid.

In an actual trilateral cycle, there are restrictions placed on the fluids. Based on the assumptions used in this study, the working fluid pressure and temperature at the heater outlet and expander inlet in the trilateral cycle can approach, but not exceed the values at the critical point. In the idealized trilateral cycle, the temperature of the working fluid entering the expander is less than the brine temperature by the selected approach temperature. When the brine inlet temperature increases relative to the working fluid critical temperature, the cycle irreversibilities in an actual cycle will increase.

The specific heat of the working fluid typically increases appreciably near the critical point. This results in a deviation from the idealized parallel heating curves, increasing the irreversibilities in an actual trilateral cycle. As the resource temperature increases, these two effects and constraints are minimized by the proper selection of the working fluid (by selecting fluids with higher critical temperatures).

The liquid-dominated geothermal resource is typically saturated with quartz. As the brine cools the quartz may precipitate as amorphous silica on piping and heat exchange surfaces. To prevent silica precipitation, a minimum brine temperature is established (based on silica solubility with temperature). In the ideal trilateral cycle, the brine can be cooled to a temperature equal to the sum of the working fluid inlet temperature and the selected approach temperature. For this study, the working fluid enters the heater at approximately the condensing temperature is 100°F. With an assumed approach temperature of 10°F, the temperature of the brine leaving the heater in the ideal trilateral cycle would be about 110°F. Using a generic calculation of the silica precipitation limits, at resource temperatures greater than ~308°F, the ideal 110°F outlet temperature would be less than the minimum value to prevent silica precipitation. One would then expect silica to scale the ideal cycle's heat exchange surfaces. In order to prevent silica precipitation, larger approach temperatures for the heaters would be used to increase the brine outlet temperature. Raising the approach temperature increases the cycle irreversibilities and adversely affects the power output.

Working Fluids and Physical Property Models

Smith and da Silva (1994) investigated numerous organic compounds as possible working fluids in a trilateral cycle, and examined temperature-entropy diagrams for 36 different fluids. They used the Redlich-Kwong-Soave equation of state to calculate thermodynamic properties for these fluids and found that both n-pentane and neopentane had what they termed suitably shaped saturation curves. They conducted experiments to measure the bubble point and dew points of these fluids and confirmed that these values were accurately predicted by the calculations.

The ASPEN PLUS model allows the use of different equations of state to model the fluid properties in the components being simulated. For this study, three different physical property models in ASPEN were used: the ideal gas law was used to model the cooling air used in the process, the 1967 ASME Steam Table correlations were used for the brine stream, and the Peng-Robinson property set was used for the working fluid. For this study, the following 20 fluids were investigated: propane, n-butane, isobutane, water, n-heptane, n-hexane, 2-methyl pentane, 3-methyl pentane, 2,2 dimethyl butane, 2,3 dimethyl butane, n-pentane, isopentane, neopentane, ammonia, Refrigerant 160, Refrigerant 150, Refrigerant 134a, Refrigerant 130, Refrigerant 40, and Refrigerant 30.

As previously indicated, to minimize the cycle irreversibilities in a trilateral cycle, it is desirable that these fluids have relatively constant specific heats and no temperature restriction. As defined in this study's assumptions, the temperature of the working fluid entering the expander in a trilateral cycle is less than the critical temperature. In order to minimize the impact of this temperature restriction, the critical temperature of the selected working fluid should be no less than 10°F (i.e., the value of the desired approach temperature) lower than the resource temperature. It is possible to use working fluids with critical temperatures that are much less than the resource temperature; however, the trilateral cycle with these fluids would have higher irreversibilities and lower performance.

Expander Efficiency

Various devices have been investigated for use in expanding fluids in the two-phase region. These devices can be classified into five broad categories: Lysholm expanders, impulse expanders, total flow turbines, total flow systems, and Hero expanders. Lysholm expanders, also called screw or helical expanders, consist of interlocking, counter rotating, helical rotors that rotate as the fluid is expanded along the axis of the rotors. Impulse turbines use a nozzle to expand the fluid against rotor blades arranged on the outer diameter of a disc; impingement of the fluid on the rotors causes the disc to turn and generates power. Total flow turbines separate saturated liquid and vapor by centrifugal forces within the rotor; each phase is then expanded through separate reaction nozzles in the rotor. Total flow systems, on the other hand, employ a separator to remove the liquid phase before expanding the vapor through a conventional turbine. Hero turbines introduce the working fluid along the hollow axis of the device and expand the fluid radially through nozzles; flow through the nozzles imparts torque to the device and spins the turbine. No reference was found for the investigation of total flow in the radial-inflow, reaction turbine used in a number of conventional binary power plants.

Measured values of isentropic efficiency for these expanders vary widely and depend on the type of expander, the expansion ratio, and the working fluid being used. Efficiency values of 50-70% were measured by Yoshida et al. (1990) for Refrigerant 11 using a screw expander at 90°C. Nenov (1993) measured an efficiency of 65-75% using cryogenic air in a Lysholm expander. Values of 57% were reported by Elliott (1982) for Refrigerant 22 in an impulse turbine at 17°C. Fabris (1993) has devised an expander with up to 75% efficiency that can accommodate two-phase fluids at the temperature range of interest for geothermal applications, but no working model has been developed to support these claims.

Comparative Rankings of Working Fluids

The results are presented in Table 1, which shows the working fluids in a comparative ranking based on the highest net power, lowest expansion ratio, and highest critical temperature. As can be seen, no single fluid shows the best performance in all categories.

Comparison with Conventional Binary Cycle

In order to determine the conditions under which the trilateral cycle technology would have an advantage over the binary cycle for recovering energy from a low temperature resource, three different comparisons were made of the performance of these two cycles. First, the performance of the two cycles was compared with identical heat input conditions and heat sink temperature conditions using the assumption listed previously. Second, performance was compared with identical heat exchanger sizes and brine and air conditions. Third, performance was compared for a range of trilateral cycle expander efficiencies. Calculations for both cycles were made at 320°F, the highest temperature considered in this study for the trilateral cycle calculations. This temperature produces the most favorable results for the binary cycle calculations. Performance comparisons made at lower temperatures would likely show a greater advantage for the trilateral cycle. The binary cycle performance was evaluated using isobutane because it is a working fluid typically used in geothermal applications. Calculations with the trilateral cycle used n-pentane, which had resulted in high net power values during preliminary calculations with the trilateral cycle.

Performance Comparison Using the Same Heat Input Conditions and Heat Sink Temperature

The procedure for this comparison was to first model the binary cycle and then using the same heat input and sink temperatures, brine flow rate, expander efficiency and heat exchanger approach temperatures, model the performance of the trilateral cycle. Results of the calculations show that the trilateral cycle could produce 15% more power from the same amount of brine. This higher power reflects the more efficient utilization of the geothermal resource, but this greater heat recovery requires that the size of the heater and condenser be increased by 86% and 17%, respectively.

Performance Comparison Using Same Equipment Sizes and 320°F Resource Temperature

In this comparison the trilateral cycle performance was evaluated using the heat exchanger sizes (UA values), brine flow rate, expander efficiency and cooling air flow rate derived for the binary cycle. Calculations show that for these conditions, the trilateral cycle produces approximately the same amount of net power as the binary cycle, but would operate at a lower turbine inlet pressure (465 psia vs 251 psia).

Performance Comparison Using Variable Expander Efficiency

As indicated previously, the trilateral cycle requires an expander that is capable of efficiently extracting the energy from the expansion of a two-phase fluid. The isentropic efficiency for two-phase expanders has not been established, but is expected to be less than that for a conventional turbine. In order to evaluate the impact of the expander efficiency on the relative performance of the trilateral cycle, its cycle performance was evaluated for a range of assumed turbine efficiencies. For this comparison, both cycles were modeled using the same heat input and sink temperatures, brine flow rate, and heat exchanger approach temperatures. (The second cycle comparison indicated that for equivalent heat exchanger UA's and air flow, the cycles would have similar performance for equivalent expander efficiencies.) This comparison indicated, that for the conditions evaluated the trilateral cycle would require a minimum isentropic expander efficiency of about 76% in order to match the performance of a binary cycle with a 85% efficient expander.

Effect of Ambient Air Temperature

The trilateral cycle, as described in this paper, uses an air-cooled heat exchanger to condense the working fluid exhausting the expander. Calculations determined the temperature elasticity, which is defined as (Δ power/power)/(ΔT/T), for air temperatures ranging from 0 to 100°F. As expected, the net power increased for lower ambient air temperatures. The magnitude of calculated elasticity increased with increasing ambient air temperature (-4 to -7 over this temperature range). This evalu-

Table 1. Comparative Rankings of Various Working Fluids (fluids listed in descending order of acceptability)

Net Work (kW) 200°F		Net Work (kW) 320°F		Expansion Ratio (range) 200-320°F		Critical Temperature (°F)	
Ammonia	(239)	R-30	(1449)	Propane	(7-8)	Water	(705)
R-160	(232)	n-Pentane	(1441)	R-134a	(9-12)	R-130	(701)
isopentane	(231)	isopentane	(1438)	R-40	(10-16)	n-Heptane	(513)
n-Pentane	(231)	2, 2 dimethyl butane	(1436)	Ammonia	(11-16)	R-150	(482)
R-30	(230)	2, 3 dimethyl butane	(1426)	isobutane	(14-22)	R-30	(458)
neopentane	(229)	R-160	(1426)	n-Butane	(20-33)	n-Hexane	(454)
n-Butane	(227)	R-150	(1425)	neopentane	(25-45)	3 methyl pentane	(448)
2, 2 dimethyl butane	(223)	2 methyl pentane	(1422)	R-160	(26-49)	2, 3 dimethyl butane	(440)
isobutane	(220)	neopentane	(1419)	isopentane	(41-78)	2 methyl pentane	(436)
2, 3 dimethyl butane	(218)	3 methyl pentane	(1418)	n-Pentane	(52-101)	2, 2 dimethyl butane	(420)
R-134a	(218)	n-Hexane	(1405)	R-30	(52-105)	n-Pentane	(386)
R-150	(217)	n-Butane	(1401)	2, 2 dimethyl butane	(75-153)	isopentane	(369)
2 methyl pentane	(216)	Water	(1388)	R-150	(88-183)	R-160	(369)
R-40	(211)	Ammonia	(1372)	2, 3 dimethyl butane	(92-192)	neopentane	(321)
3 methyl pentane	(209)	isobutane	(1367)	2 methyl pentane	(99-205)	n-Butane	(306)
n-Hexane	(207)	R-40	(1331)	3 methyl pentane	(105-223)	R-40	(290)
Propane	(191)	n-Heptane	(1266)	n-Hexane	(121-257)	isobutane	(275)
n-Heptane	(161)	R-134a	(1005)	n-Heptane	(220-523)	Ammonia	(270)
Water	(160)	R-130	(975)	R-130	(335-1068)	R-134a	(214)
R-130	(42)	Propane	(896)	Water	(621-1569)	Propane	(206)

ation indicates the effect of ambient air temperature on performance is more significant at higher ambient air temperatures. Elasticity values were approximately the same for both the binary and trilateral cycles (about -5.2 at 60°F).

References

Elliott, David G., December 15, 1982, ATests of a Two-Stage, Axial-Flow, Two-Phase Turbine," Jet Propulsion Laboratory, DOE/ER-10614-2.

Fabris, Gracio, August 17, 1993, ATwo-Phase Reaction Turbine" U.S. Patent No. 5,236,349.

Nenov, N. T., Development of Lysholm Expander, January 31-February 4, 1993, ACryogenic Processes and Equipment Proceedings of the 16th Annual Energy - Sources Technology Conference and Exhibition," Houston, TX, sponsored by ASME, pp. 49-53.

Smith, I. K. and R. Pitanga Marques da Silva, 1994, ADevelopment of the Trilateral Flash Cycle System Part 2: Increasing Power Output with Working Fluid Mixtures," Proc Instn Mech Engrs, vol 208, pp. 135-144.

Yoshida, Takao, Kurisu, Masato, Kawabe, Hidehiko, and Rodama Yoshio, August 1990, AA Small Electric Power Generation System for a Thermal Spring," Geothermal Resources Council Transactions, Vol. 14, Part II, pp. 1071-1078.