New Turbines to Enable Efficient Geothermal Power Plants

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Keywords

Geothermal utilization, low temperature geothermal, efficiency, exergy, thermodynamic cycle, binary cycle, Kalina cycle, Variable Phase cycle, organic Rankine cycle, radial outflow turbine, axial impulse turbine

ABSTRACT

Efficient resource utilization is critical in the viability of geothermal projects. Novel thermodynamic energy conversion cycles exist that are superior to the traditional organic Rankine cycle. Two new turbines have been developed that enable the economic and efficient implementation of these cycles that maximize the geothermal resource utilization. The turbines, the Euler Turbine and the Variable Phase Turbine, can increase power production by as much as 30-50% from low temperature resources and enhanced geothermal resources when compared to commercially available organic Rankine cycles.

The Euler Turbine is a radial outflow turbine originally developed for energy recovery in steam systems. Commercial units of 275 kWe capacity are operating on steam, some with isentropic efficiencies above 80%. The Euler Turbine is also currently being implemented in a 600 kW Kalina cycle in Bruchsal, Germany.

The Variable Phase Turbine uses axial impulse turbine technology that is well adapted to the expansion of transcritical or flashing liquid flow. The high isentropic efficiency, typically greater than 80%, enables a liquid heat exchanger cycle[1] to be used, avoiding the pinch point limitations of the evaporator in an organic Rankine cycle. Because this cycle can use a significantly lower exit temperature, significantly more energy can be extracted from a given resource. The resulting power advantage of 30-50%, leverages the total development cost of the geothermal project. A 40% increase in power production from a given geothermal resource lowers the total capital cost—including exploration, drilling, and surface plan— by 29%.

Results of analytical models for cycles utilizing the Euler Turbine and Variable Phase Turbine will be presented along with geothermal power plant designs for both. Additionally, experimental results of operating the first two-phase closed cycle power system with a Variable Phase Turbine will be presented.

Introduction

Low temperature geothermal resources, enhanced geothermal resources and separated brine from flash plants, are huge sources of energy. However, because of their characteristically low temperature, these projects and power systems have a high cost per installed kilowatt of power. To produce power from these resources the energy conversion system must maximize the conversion of available energy to power.

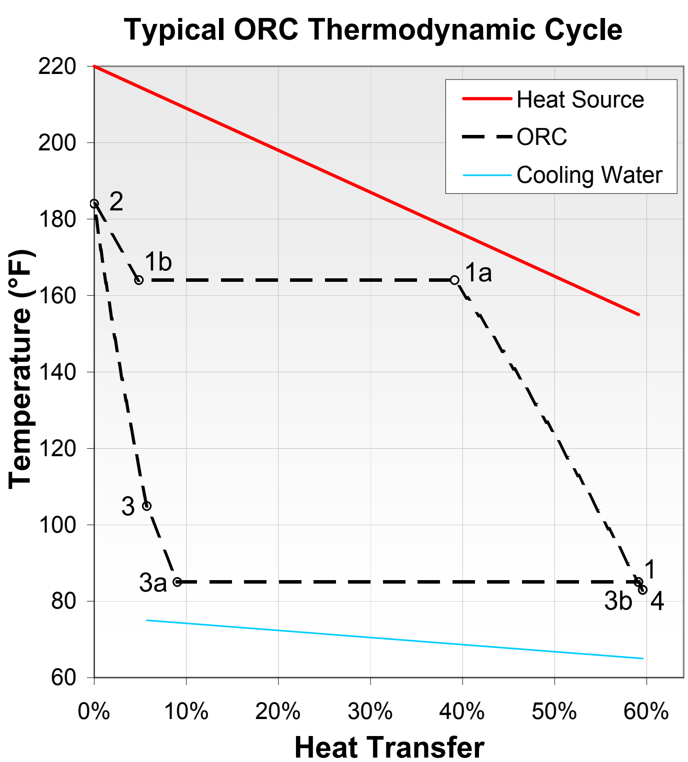


Figure 1. ORC temperature profile.

A common characteristic of these energy sources is that as heat is transferred to the power conversion system, the temperature decreases nearly linearly (sensible heat). This behavior can be contrasted to evaporating flows, which absorb heat at a nearly constant temperature, accompanied by a phase change (latent heat). This is characteristic of organic Rankine cycles.

Figure 1 shows an example ORC operating with R134a. The geothermal heat source enters the vaporizer at 220 °F and exits at 155 °F. Liquid R134a exits the refrigerant pump (1) and is heated to boiling (1a) and then entirely boils in the vaporizer (1b) and the vapor is subsequently superheated (2). The superheated vapor is expanded through a turbine (3) and is then condensed (3a and 3b) and subcooled (4), at which point it is pressurized in the refrigerant pump to close the cycle.

The ORC creates a pinch point between (1a) and the cooling geothermal flow that limits the geothermal water return temperature. The ideal thermodynamic cycle would eliminate this boiling pinch point to recover more heat from the geothermal resource while efficiently converting the recovered heat into electricity. Until now, turbine technology has been a barrier to usage of improved cycles.

Euler Turbine

Pressure reducing valve (PRV) stations are a large source of wasted potential energy in steam systems, converting pressure energy into heat produced by frictional dissipation. The Euler Turbine was designed to capture this energy in an efficient, compact package (Figure 2) which can be applied under a wide range of conditions to steam and gas expansions. Commercial units are operating with some reaching isentropic efficiencies above 80%. Previous state-of-the-art commercial steam turbines of comparable power have isentropic efficiencies of 50% or less.

The Euler Turbine is a radial outflow reaction turbine consisting of a nozzle row, blade row, and diffuser. Figure 3 shows the flow-path through the turbine. Vapor enters axially and is turned radially outward before entering the nozzle row. The flow is accelerated as the pressure drops to an intermediate pressure at the entrance to the rotor. In the rotor, the flow continues to accelerate as it moves radially outward and is directed tangentially in the direction opposite rotation prior to exiting the rotor. A vaneless diffuser recovers the remaining kinetic energy in the flow before it exits the turbine.

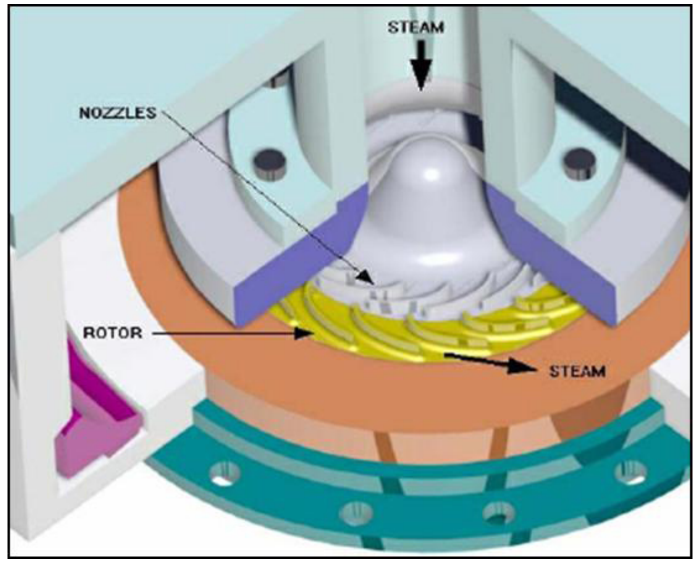


Figure 3. Euler Turbine flow-path.

Figure 2. Euler Turbine package in parallel with a PRV station.

The Euler Turbine was designed to handle saturated steam at the turbine inlet, which can result in as high as 10% moisture at the rotor exit. Unlike radial inflow turbines, centrifugal forces in the Euler Turbine pull moisture and contaminants away from the nozzle-rotor interface. Thus the design is inherently erosion resistant, enabling its wide use with expansions that drop into the wet region. The Euler Turbine utilizes two-dimensional vane and blade profiles, giving stout, strong blades and simple, low-cost construction (Figure 4). Another benefit of the radial outflow design is a reduction in operating speed to approximately half that of comparable radial inflow machines, reducing the size and losses

Figure 4. Euler Turbine rotor.

of a gearbox while also improving rotordynamics. In radial-inflow turbines, pressure ratios higher than 4:1 result in designs that require multiple expanders and greatly increased complexity and size. A two-stage version of the Euler Turbine has been designed and tested. Both rows of blades are machined onto a single blisk, resulting in a compact machine with a pressure ratio up to 10:1.

Euler Turbine: Application to the Kalina Cycle

The Kalina cycle was developed as in improvement to the organic Rankine cycle for sensible heat sources. Operating with a multiple component fluid—typically ammonia and water—the Kalina cycle employs variable temperature boiling in the evaporator. The variable composition during the boiling produces a "glide" effect which reduces the pinch point limitation when compared to an ORC.

Upon leaving the evaporator, the mixture is not entirely boiled and so a separator is required. The vapor stream coming from the top of the separator is expanded through a turbine. Moisture forms as the saturated vapor mixture is expanded. The presence of moisture makes the Euler Turbine desirable because of its rugged design. The liquid stream from the bottom of the separator goes through a heat exchanger, boiling a fraction of the incoming refrigerant and then rejoins the turbine exhaust. The exhaust flow is then condensed and subcooled. The multiple component fluid also undergoes variable temperature condensation in the condenser. Overall, the Kalina cycle offers an efficiency advantage as compared to the standard ORC[2].

An Euler Turbine was chosen for a Kalina cycle plant in Bruchsal, Germany. Based on the design point data (Table 1), the shaft power is 610.5 kW and the electrical power is 557.4 kWe for a shaft efficiency of 82.4% and electrical efficiency of 75.3%. These efficiencies include the energy loss in the control valve. The exit vapor quality from the turbine is 96%.

The turbine rotor is made of titanium and weighs 13 lb with a 10" outer diameter. It spins at 28,000 rpm and is connected to an induction generation by a gearbox (Figure 5). The turbine, lube oil system, and junction box with cables were assembled on a single skid to minimize on-site installation and wiring. The turbine-generator assembly was tested and synchronized at the Energent factory. Figure 5 shows the unit installed at the geothermal site. This unit is scheduled for startup in July 2009.

Table 1. Euler Turbine for Kalina cycle.

Ammonia Content	Mass %	92.7
Mass flow	kg/s	4.83
Inlet temperature	°C	115.3
Inlet pressure	bar a	20
Outlet pressure	bar a	7.81

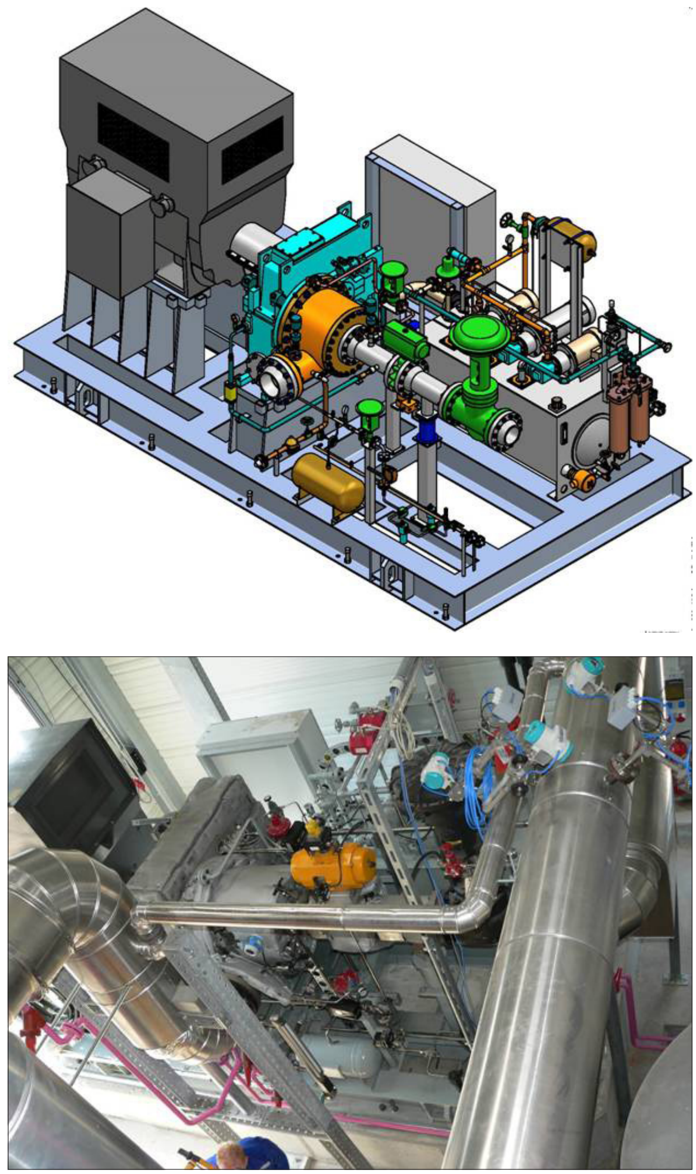
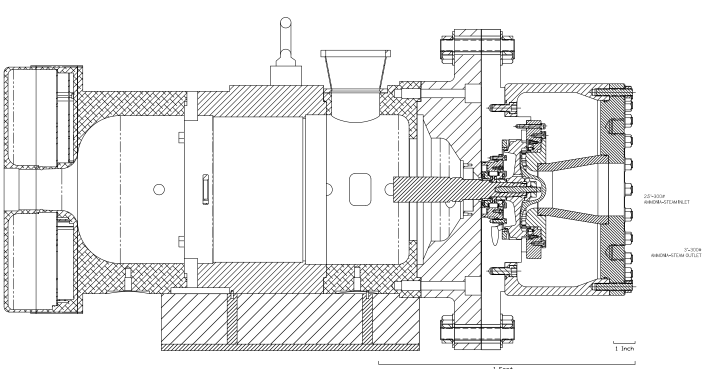


Figure 5. Model (top) and Installation (bottom) of the Euler Turbine skid for Kalina cycle geothermal power plant.

Another Kalina cycle application is for use in a planned mini-geothermal plant in Otari, Japan. This Euler Turbine will be equipped with a high speed generator (56,000 rpm, 65 kW) supported by magnetic bearings in lieu of a gearbox and synchronous generator (Figure 6). The high speed generator will both increase efficiency and allow for



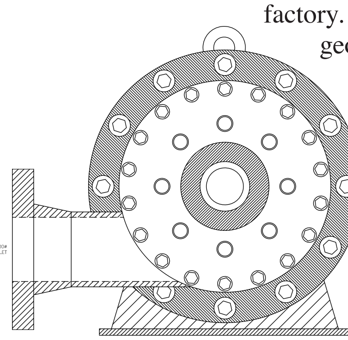


Figure 6. High-speed Euler Turbine for Kalina cycle application in geothermal power plant.

speed variation to maximize performance over a large range of operating conditions.

The Euler Turbine can also be incorporated into ORC designs in place of a radial inflow turbine. For a waste heat application studied, the use of a two-stage Euler wheel in an ORC enabled direct drive of a 300 kW, 3,000 rpm induction generator, eliminating the gearbox. The proposed design would incorporate a hermetic generator submerged in the refrigerant working fluid. This would allow for removal of the dynamic seals that are often troublesome.

Variable Phase Turbine

The Variable Phase Turbine (VPT) is comprised of a set of individual, fixed nozzles and an axial impulse rotor. The two-phase nozzle (Figure 7) is the thermodynamic energy conversion element of the VPT. Enthalpy is converted to two-phase kinetic energy in a near isentropic expansion. Expanding gas breaks up the liquid phase into small droplets. Momentum is transferred from the gas to the droplets by pressure and shear forces. The small diameter of the droplets results in a close coupling of the gas and liquid, producing efficient acceleration of both phases. The inlet to the nozzle can be liquid, two-phase, supercritical, or vapor.

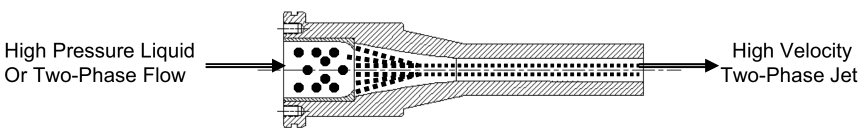


Figure 7. Schematic of two-phase VPT nozzle.

Two-phase kinetic energy is efficiently converted to shaft power by reversing the direction of the tangential component of the flow velocity in an axial impulse turbine. The turbine is designed with a special blade contour to minimize momentum and friction losses of the liquid impinging on the surface and flowing over the surface (Figure 8). A true impulse turbine with no reaction or pressure drop in the rotor, the runaway speed is limited to no more than the two-phase jet velocity and axial thrust on the rotor is minimized. Maximum droplet impact velocity for typical expansion conditions is 300-500 feet per second. No erosion results, as the threshold impact velocity for erosion of the titanium alloy wheel is in excess of 1,000 feet per second.

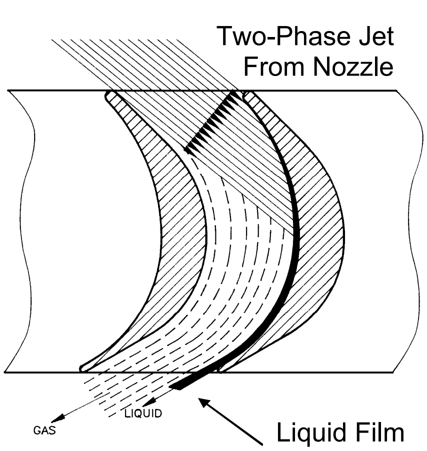


Figure 8. Schematic of flow path in two-phase VPT blades.

The arrangement of the VPT (Figure 9) is similar to a conventional axial impulse turbine. The nozzles are inclined at a tangential angle to the rotor. The two-phase impulse wheel is a blisk—that is, an integrally bladed rotor—which has low stress and incorporates a shroud to control the location of any stray liquid. Liquid leaving the rotor separates onto the duct walls.

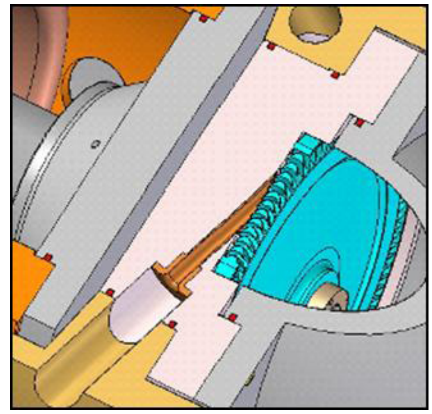


Figure 9. Variable Phase Turbine nozzle and rotor arrangement.

Two-phase nozzle efficiency is typically between 90% and 97% and is influenced strongly by the surface tension of the working fluid and the vapor density at the condensing pressure. Standard refrigerants that are used in low temperature geothermal are ideal in these aspects because of their low surface tension and high vapor density.

Rotor efficiency is typically between 78% and 85% and is influenced strongly by the vapor quality at the exit of the nozzle.

Variable Phase Turbine: Experience

Refrigeration

The two-phase impulse turbine of the type described is the only two-phase turbine with extensive commercial experience. Two-phase axial impulse turbines designed by Energent staff have been in refrigeration service for many years. Over 75 units have been installed in Carrier commercial chillers. The earliest units have operated for 10 years with no required turbine maintenance. One of these 500 Ton chillers (the 19 XRT model) is shown in Figure 10. In this application, the two-phase turbine replaces the two-phase expansion valve and generates 15 kW from the flashing refrigerant. The result is a 7-8% improvement in the chiller system efficiency[3].

Figure 10. Carrier 19 XRT chiller with two-phase turbine.

Figure 11 is a photograph of the two-phase impulse wheel and nozzle assembly from a larger refrigeration installation. The nozzles are removable inserts. The turbine wheel, to the right, has blisk construction.

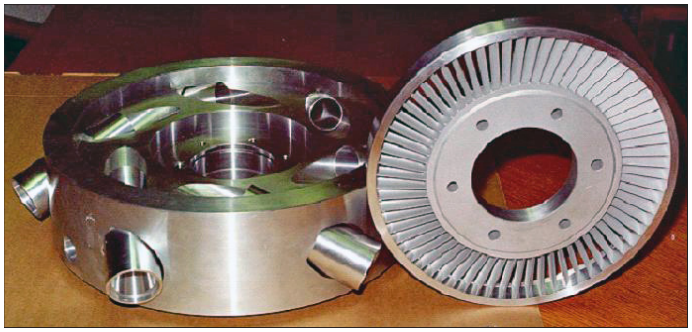


Figure 11. Two-phase refrigeration nozzle assembly and rotor.

Low Temperature Testing

Figure 12 is a photograph of a Variable Phase Turbine system pilot plant. This is the world's first closed cycle two-phase power plant. The VPT shown in the figure has a vertical axis and operates with flashing refrigerants. Testing with flashing R227ea and R245fa refrigerants at the 7 kW level verified the design codes utilized for predicting performance. R134a has not yet been tested in the pilot plant. Refrigerant temperatures exiting the heater have been tested as high as 250 °F (limited by the heater capacity). In addition to performance testing, the unit has been operated for 150 hours to determine whether incipient erosion or cavitation would occur. The wheel showed no signs of either erosion or cavitation.

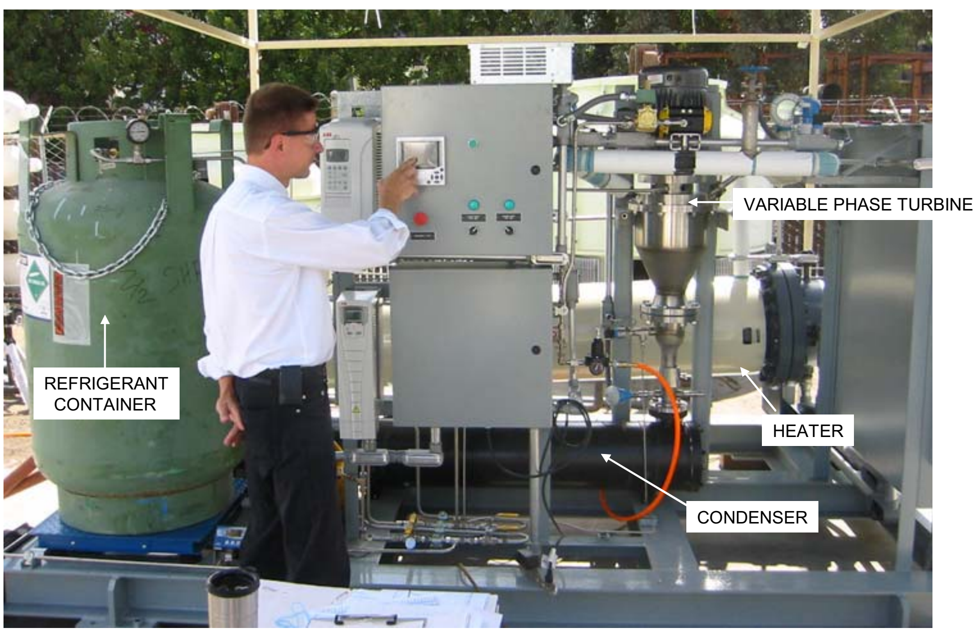


Figure 12. Variable Phase Turbine operating in pilot plant.

Variable Phase Cycle

The Variable Phase cycle (VPC), also called the triangular or trilateral cycle, is the ideal thermodynamic cycle for low temperature sensible heat recovery[4]. Liquid working fluid is pressurized and then heated in the heat exchanger with no vaporization. The heated, pressurized liquid leaving the heat exchanger is directly expanded in a two-phase expander. The low pressure fluid is condensed, closing the cycle.

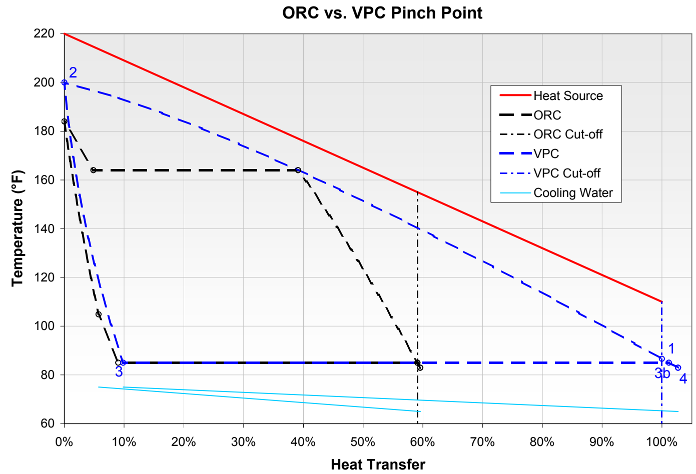


Figure 13. VPC and ORC temperature profile comparison.

Consisting of a pump, liquid heat exchanger, turbine, and condenser the VPC is a simple system with lower cost elements than most ORC systems. A significant advantage of this energy conversion system is the heat exchanger. Instead of a heat recovery boiler (which has a large separator drum and extensive operating and maintenance labor), a counter-current compact liquid heat exchanger is used to recover the geothermal energy. The boiling "pinch point" restriction is eliminated (Figure 13).

In the scenario shown, the ORC only captures 59% of the heat that is extracted by the VPC from the resource. This analysis assumed an adiabatic pump efficiency of 77%, an adiabatic turbine efficiency of 85% for the ORC turbine and 80% for the VPC turbine, and a gearbox efficiency of 98% for the ORC. The VPC generated 35% more net electricity than the ORC.

The lack of an efficient, reliable two-phase turbine has prevented prior use of the VPC.

Variable Phase Cycle: Analytical Comparison to ORC

A study was conducted to compare the VPC to the ORC. The fluid chosen for the study was R134a, as its low critical temperature (214 °F) and widespread use are conducive to its use in low temperature geothermal. The component efficiencies were selected by an independent party familiar with typical ORC performance (Table 2, overleaf). VPT efficiencies were calculated for the VPC expander model.

Results are shown in Figures 14a, 14b, and 14c (overleaf) for 250 °F, 300 °F, and 350 °F geothermal inlet temperature,

Table 2. Component efficiencies and parameters for VPC/ORC study.

Heat Exchanger Pinch Point	10	°F
Heat Input (@ 160 °F return)	100	MMBTU/hr
ORC expander shaft efficiency	82%	
VPT nozzle efficiency	92-97%	Calculated
VPT rotor efficiency	78-85%	Calculated
Pump shaft efficiency	77%	
Generator Efficiency	97%	
Gearbox Efficiency (ORC)	98%	
Recuperator (optional) pinch	60	°F
Pump Motor Efficiency	95%	

respectively. Net electrical power is shown without taking into account the parasitic cooling load which will be site dependent and identical for an ORC or VPC at a given return temperature. Clearly, the power increases at the geothermal return temperature is reduced. The VPC is able to produce more power than the ORC under almost all conditions and shows strong benefits as the return temperature is lowered.

As with all geothermal installations, the minimum return temperature—which is dependant on water chemistry—must be determined. Novel heat exchanger designs and cleaning techniques have been developed which reduce the minimum return

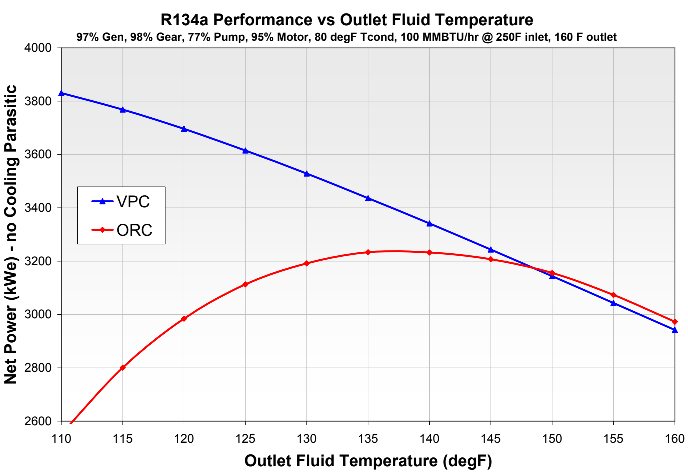


Figure 14a. VPC vs. ORC for R134a - 250 °F geothermal inlet temperature.

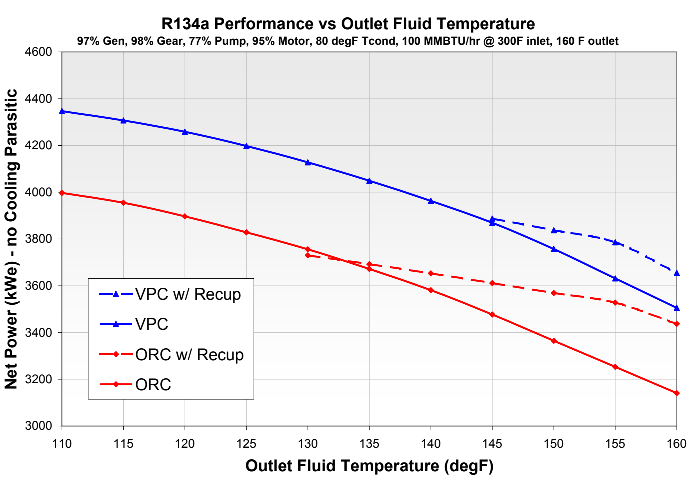


Figure 14b. VPC vs. ORC for R134a - 300 °F geothermal inlet temperature.

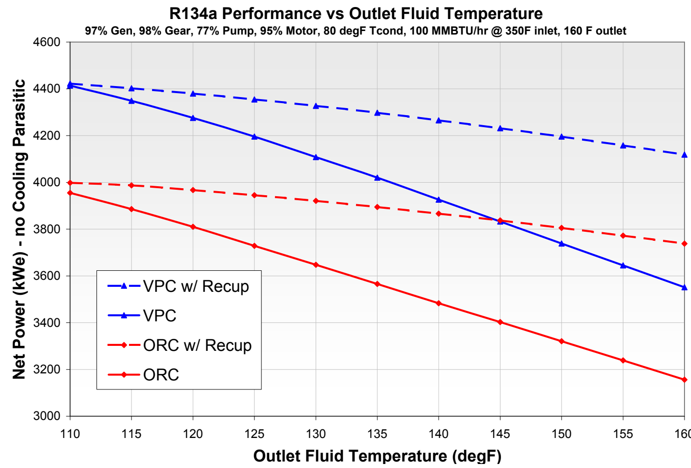


Figure 14c. VPC vs. ORC for R134a - 350 °F geothermal inlet temperature.

temperature and should be considered when designing the plant. Also, the availability of direct uses of the warm return water will affect the optimum design point.

Variable Phase Turbine: Application to the Variable Phase Cycle

Designed for two-phase expansions, the Variable Phase Turbine allows for efficient utilization of the VPC. The VPT is also suitable for supercritical versions of the VPC.

Figure 15 is a schematic of the Variable Phase cycle applied to geothermal power generation.

Geothermal fluid enters the heat exchanger where the available heat energy is transferred into the energy conversion working fluid. After heating in the heat exchanger the liquid is flashed in two-phase nozzles which are integral parts of the hermetic Variable Phase Turbine assembly. The high momentum, low velocity two-phase stream drives the turbine rotor at synchronous speed to the generator. This eliminates the need for the expensive gearbox required for ORC vapor turbine systems and thereby improves reliability and reduces maintenance.

The use of refrigerant working fluids in the VPC enables lubrication and cooling of the generator by the working fluid. The lube oil system required for ORC systems is eliminated, as are seals. The result is a zero emissions hermetic assembly

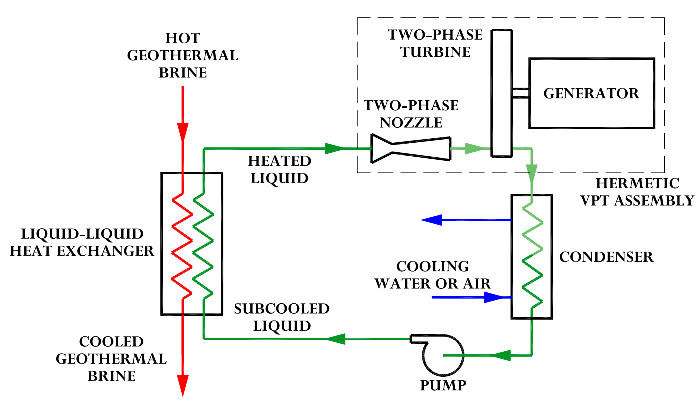


Figure 15. Variable Phase cycle process flow diagram.

without the expense and reliability problems of those components for an ORC.

The exhaust from the turbine is condensed in a compact condenser. Standard refrigerant condensers are used, enabling low cost and compact size. The condensate is then pressurized by a hermetic pump and circulated through the liquid heat exchanger to close the cycle.

The lack of a phase change in the heat exchanger makes the VPC stable and simple to control.

Variable Phase Cycle: Application to the Commercial Geothermal Market

Figure 16 is a compact waste heat recovery system designed under a DOE study for recovery of heat from a brine stream at 245 °F. The unit was designed to be factory assembled and tested followed by shipping to the site and installation on pre-poured foundations.

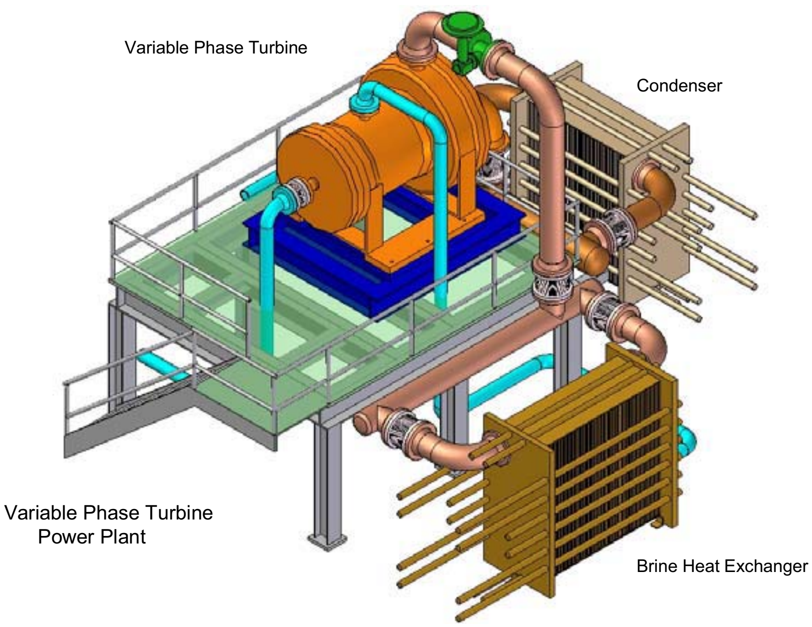


Figure 16. VPC 1 MW geothermal power plant with plate-and-frame heat exchangers.

The cost was determined for a 1 megawatt system. Turnkey price for the system, including factory assembly and checkout, site work and electrical interconnection was estimated to be $1,278,915 or $1,279/kWe. These costs are based upon the first article system. The cost can be compared with typical installed costs for ORC systems in this size range which are in the range $2,300 to $2,500/kW. Costs are reduced due to the elimination of the gearbox, lube oil system, seals and the use of a simpler heat exchanger. We believe the heat exchanger costs in particular will be further reduced via economies of scale.

The VPT has the additional advantage of being able to accommodate widely varying power levels for a single given rotor and housing design. Because the nozzles inserts are discrete, they can be blanked off or changed out for nozzles with different profiles. Discrete nozzles allow for variations in resource production without bypassing flow or operating at part-load efficiency. The range of conditions that can be accomplished with a particular turbine and rotor design is thus quite large and a set of modular power skids can be developed that are quickly deployable with lower cost. Factory assembly and checkout would be performed to reduce on-site startup time and costs.

The VPC utilizing a VPT is simple and stable which are two critical factors in achieving a quick, successful start-up of a geothermal power plant. The elimination of the gearbox increases efficiency and reliability, reduces complexity and capital cost, and eliminates the associated lube-oil subsystem present in typical organic Rankine cycle systems.

The Variable Phase cycle is able to generate more electricity from a given geothermal well. Increased electrical production decreases all other costs on a per kW basis. Consider a potential project where the exploration, drilling and surface plant costs of a project were $6,000,000. An organic Rankine cycle may produce 1500 kWe whereas a Variable Phase cycle could produce 2000 kWe with the same resource, thus bringing the cost per kW down from $4,000/kWe to $3,000/kWe. This cost reduction might enable an otherwise economically nonviable project.

Summary

Two novel turbines have been developed that enable the economic and efficient implementation of novel thermodynamic cycles that maximize the geothermal resource utilization: the Euler Turbine and the Variable Phase Turbine. These turbines improve resource utilization through a combination of increased system efficiency, increased robustness and reliability, reduced maintenance requirements, leveraging better $/kW ratios by reducing system component count and complexity, and increasing the amount of energy that can be extracted from a given resource.

Experience in the steam pressure let-down systems as well as application to the Kalina cycle have proven the performance and versatility of the Euler Turbine.

Use of the Euler Turbine with the Kalina cycle or ORC provides:

- Moisture and contaminant resistance with no erosion.
- Two-dimensional vane and blade profiles, giving stout, strong blades and simple, low-cost construction.
- Reduction in operating speed to approximately half that of comparable radial inflow machines, reducing the size and losses of a gearbox while also improving rotordynamics.
- Multiple stages on a single, compact blisk for high pressure ratios.

Based on analytical and experimental test results, the power advantages and performance of the Variable Phase cycle have been validated.

The advantageous features of the Variable Phase cycle utilizing the Variable Phase Turbine are:

- Efficient conversion of liquid, two-phase, supercritical, or vapor pressure energy.
- Increased power recovery from a given geothermal resource.
- Reduced cost by the simplification and elimination of components required in an ORC.
- Increased reliability through the elimination of high maintenance items required by an ORC such as the waste heat boiler, gearbox, seals and lube oil system.
- A compact, modular design resulting from the use of compact heat exchangers, enabling factory assembly and checkout and reduced installation costs at the site.

Acknowledgements

We would like to recognize Lance Hays for his dedication to the creation and development of the Euler Turbine and Variable Phase Turbine technologies.

References

1 Hays L., 1977, "Biphase Turbines for Diesel Bottoming," 12th IECEC (779077), 473-480.

2 Mlcak, H.A., 1996, "An Introduction To The Kalina Cycle," ASME Joint Power Generation Conference, Houston, Texas.

3 Hays L., and J. Brasz, 1996, "Two-Phase turbines for Compressor Energy Recovery", International Compressor Engineering Conference, Purdue University, Purdue.

4 DiPippo R., 2007, "Ideal Thermal Efficiency for Geothermal Binary Plants", *Geothermics,* V. 36, 276-285.