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ABSTRACT

In this paper, the use of liquid flooding is examined to create a high efficiency Ericsson Power Cycle. The introduction of significant amounts of liquid into the compression and expansion processes of a gas leads to quasi-isothermal behavior approximating that of an Ericsson cycle. A thermodynamic model is presented and various working fluid pairs are examined under operating conditions suitable for solar thermal power generation. The Liquid-Flooded Ericsson Cycle (LFEC) can be manufactured with fixed volume ratio machinery currently mass produced for the refrigeration industry. In this manner low cost, distributed solar thermal generation can be promoted. The thermodynamic performance of the LFEC is compared to that of other power cycles proposed for solar thermal systems. It is shown that for sufficiently high component efficiencies the Liquid-Flooded Ericsson Cycle provides higher thermal efficiencies than any other power cycle currently under consideration.

1. INTRODUCTION

The Liquid-Flooded Ericsson Cycle (LFEC), as presented by Hugenroth (2006), is a practical implementation of an Ericsson cycle which can serve as a high efficiency power block for concentrated solar power (CSP) applications. The U.S. Department of Energy (2012) has identified the increase of conversion efficiencies in the power block of CSP plants as one of the many ways to drive down the cost of these renewable energy systems. The Ericsson Cycle is a gas cycle theoretically capable of achieving Carnot efficiencies. It consists of isothermal compression and expansion with isobaric regeneration. The LFEC utilizes liquid-flooding; which is the introduction of large quantities of liquid into the gaseous working fluid. The liquid serves as a thermal reservoir absorbing heat during compression and releasing heat during expansion. In this manner near isothermal behavior can be achieved. Typical turbo-machinery is susceptible to damage when liquid is entrained in the gas stream. Fortunately equipment utilized in the air conditioning and refrigeration industry has proven reliable when operating with liquid entrainment. Fixed volume machines, such as scroll and screw compressors, represent readily available devices that can be adapted for use in the LFEC. Through proper design they can be tailored for efficient operation with flooding (Bell et al. 2012).

Results of thermodynamic modelling of the LFEC under conditions of interest to solar thermal power generation are presented in this paper. Models of competing power cycles are developed and their thermal efficiency compared to that of the LFEC.

2. CYCLE DESCRIPTION

A schematic of the LFEC is shown in Figure 1. After mixing, cool liquid and gas are simultaneously compressed from state (1) to (2). During this process the liquid is slightly warmed due to absorbing the heat of compression. The gas and liquid are then separated with the gas heading to the regenerator at point (3) and the liquid heading to the cooler at point (9) to reject the heat of compression. The regenerator allows for thermal exchange between the high and low temperature sides of the cycle. The gas passing from points (3) to (4) is warmed as it absorbs heat from the counterflowing stream returning to the cool side of the cycle from points (7) to (8). After passing through the regenerator the gas is then mixed with hot liquid and sent to the expander at state (5). During the expansion process the liquid slightly cools supplying heat to the gas, maintaining near isothermal conditions. After expansion the gas and liquid are separated, with the gas heading back to the regenerator at state (7) and the liquid heading to be pumped up to high pressure and reheated at state (12). A solar field can serve in the role of the heater and the high temperature separator can be enlarged for thermal storage allowing for natural integration of the LFEC into CSP systems. The LFEC can operate at relatively low pressures. Due to this the liquid which absorbs the heat of compression in the compressor can be easily pumped directly to a load to provide heating. In this manner the LFEC can readily function as a combined heating and power (CHP) system.

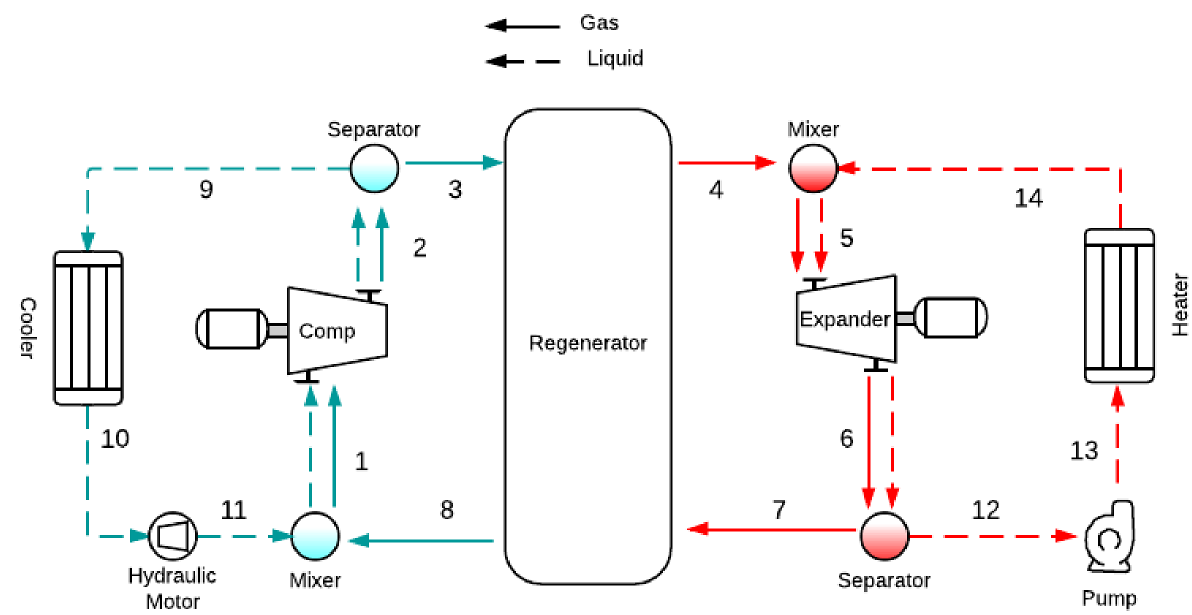

Figure 1: Liquid-Flooded Ericsson Cycle schematic

3. CYCLE MODELLING

A component based model of the LFEC was developed in order to better understand the performance of the cycle under conditions of interest to solar thermal power generation. The following assumptions were made in generating the model:

- Pressure drops in lines and heat exchangers are neglected
- Heat loss in lines are neglected
- Gas is non-condensable in liquid and separation is complete
- When mixed, liquid and gas are in thermo-mechanical equilibrium
- All rotating components are adiabatic
- Mixing and separation are adiabatic

Thermodynamic properties at each point in the cycle were calculated utilizing a combination of equations of state included in Engineering Equation Solver (EES) (Klein 2012) and thermophysical property data. By specifying two independent properties each state could be defined. In sections of the cycle where liquid and gas are mixed, thermodynamic properties were determined using a mass weighting of both the liquid and gas properties each evaluated at the same temperature and pressure. Equation (1) is an example evaluation of the mixture enthalpy.

$$H_{mix} = m_{gas}\left(h_{gas}(T,P)\right) + m_{liquid}\left(h_{liquid}(T,P)\right) \quad (1)$$

3.1 Component Models

The heat transferred in the heater and cooler was determined by evaluating the enthalpy change across each component with the outlet fixed at the source or sink temperature. The regenerator was modelled using an effectiveness method. By specifying an effectiveness, Equation (2) was used to determine the heat transferred in the regenerator.

$$\dot{Q}_{cool} = \dot{m}\,(h(T_7,P_3) - h(T_3,P_3)) \qquad \dot{Q}_{hot} = \dot{m}\,(h(T_7,P_7) - h(T_3,P_7)) \quad (2)$$

$$\dot{Q}_{regen} = \varepsilon_{regen} * MIN(\dot{Q}_{cool}, \dot{Q}_{hot})$$

The work produced or consumed by rotating components was determined by defining an isentropic efficiency to determine the enthalpy change across each device relative to an isentropic process. This procedure is straightforward for single-phase devices, such as the pump and motor. For the flooded compressor and expander numerical iteration as shown in Hugenroth (2006) was used to determine the isentropic outlet state.

3.2 Fluid Selection

A wide variety of gases could be chosen as the working fluid. The primary restriction on the choice of a gas was its ability to safely operate at elevated temperatures and not auto ignite.

Similarly the liquid selection was also limited by high temperature compatibility. Of primary concern was the substance's ability to remain in the liquid state at elevated temperatures. To some degree this could be influenced by raising the system pressure above the liquid's vapor pressure. However, various liquids undergo thermal breakdown after prolonged exposure to high temperatures imposing a cap on feasible operation temperatures. Another concern when choosing a liquid is its ability to operate over the entire temperature range of the cycle. This means that in addition to not boiling at high temperatures, it must resist solidification at low temperatures. In theory, it would be possible to use two separate liquids in the LFEC, one suited for high temperatures on the expansion side and another capable of low temperature operation on the compression side. In practice, some fluid carryover may occur through the regenerator and solidify, leading to potential damage in the compressor and blockage of the heat exchangers. For this reason, it would be preferable to use a single liquid for both high and low temperature flooding. Table 1 shows a few potential flooding liquids and their applicable operation ranges.

Table 1: Potential flooding liquid properties

Liquid	T_{min} (°C)	T_{max} (°C)	Vapor Pressure* (kPa)
Therminol VP1[A]	12	400	1320
$Na_{22}K_{78}$[B]	-2	785	0.13
Therminol 66[C]	0	370	130

*evaluated at elevated temperatures
A: Solutia Technical Bulletin 7239115C
B: BASF
C: Solutia Technical Bulletin 7239146D

4. LFEC MODEL RESULTS

Utilizing the aforementioned model, performance trends for the LFEC were generated. Unless otherwise stated, the following operating parameters were imposed on the model.

- Heat rejection temperature of 43°C[1]
- Low side pressure of 130 kPa[2]
- Regenerator effectiveness of 95%
- Component adiabatic efficiencies of 90%

- Nitrogen as gaseous working fluid
- Therminol-66 as flooding liquid

  [1] chosen to allow for dry cooling in arid regions (U.S. Department of Energy 2011)

  [2] chosen to prevent boiling of flooding agent (Solutia Technical Bulletin 7239146D)

Optimization routines available in EES were employed to maximize the cycle thermal efficiency at each operating condition. Three parameters were varied to perform the optimization. These were the compressor mass flow ratio y_c, the expander mass flow ratio y_e, and the system pressure ratio. The mass flow ratio was defined as the mass flow of liquid divided by the mass flow of gas for each side of the system. The pressure ratio was defined as the high side system pressure divided by the low side pressure.

Nitrogen was chosen as the working fluid due to its being non-toxic, abundant, and environmentally benign. Figure 2 highlights the effect of working gas selection on the performance of the LFEC. For comparison, the plot on the left shows the efficiency of each gas in a Brayton cycle; which is essentially an LFEC without flooding. The plot on the right presents the thermal efficiency of the LFEC with optimized flooding ratios. Together these plots depict the relative improvements to cycle performance through introducing flooding. The degree of this improvement varies with source temperature going from around a 2% increase in thermal efficiency at 150^{O}C to a 7% increase at 350^{O}C. There is very little difference in the thermal efficiency of the LFEC when operating with Nitrogen, Helium, or Carbon Dioxide. However, the use of the refrigerant R134a results in a significant drop in the efficiency of the LFEC. When choosing a working gas, other criteria such as compatibility with the flooding liquid and equipment should be considered in addition to cycle efficiency.

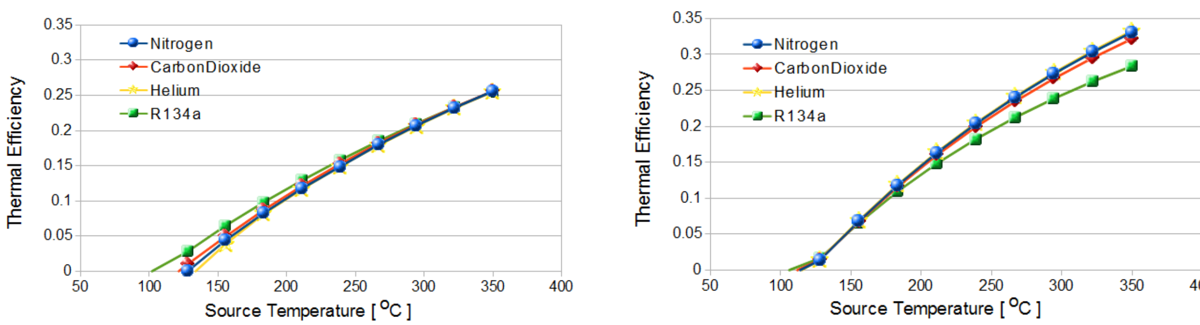

Figure 2: (Left) Thermal efficiency of regenerative Brayton cycle vs source temperature for various working fluids. (Right) Thermal efficiency of LFEC utilizing Therminol-66 vs source temperature for various working fluids.

Therminol-66 was chosen as the flooding liquid due to the widespread use of similar thermal oils in CSP plants. In addition liquid flooding has been successfully demonstrated using oil in fixed volume machines (Hugenroth 2006). The effect of the flooding liquid selection on thermal efficiency is shown in Figure 3. From the plot it can be seen that Therminol-66 provides better conversion efficiencies than molten NaK salt and Therminol-VP1 at source temperatures below 350 ^{O}C. Greater efficiencies can be achieved by operating the LFEC at higher temperatures with liquids such as molten NaK salt, as shown in section 4. The analysis below was limited to 350 ^{O}C in order to investigate other properties, excluding operating temperature, which make for an ideal flooding agent.

Figure 3 also shows the ratio of the pumping work divided by the expansion work as a function of temperature for each liquid. This value represents the relative losses associated with pumping the flooding liquid. One of the reasons for the superiority of Therminol-66 is that it has fewer losses associated with pumping. This is due in part to Therminol-66 having a larger heat capacitance than NaK as well as a lower vapor pressure than Therminol-VP1. A fluid with a larger specific heat will be able to absorb or release a greater amount of heat per unit mass. In this manner less fluid is required to be pumped in order to achieve the same isothermal effect. Hence less pumping work is required. In regards to the advantage over Therminol-VP1, the vapor pressure sets the minimum low side pressure in the system. Equation (3) depicts the pumping work for an incompressible liquid from pressure P_1 to P_2. By substituting the Pressure Ratio P_r into the equation, it becomes evident that for a given pressure ratio the pumping work increases linearly with the low side pressure P_1.

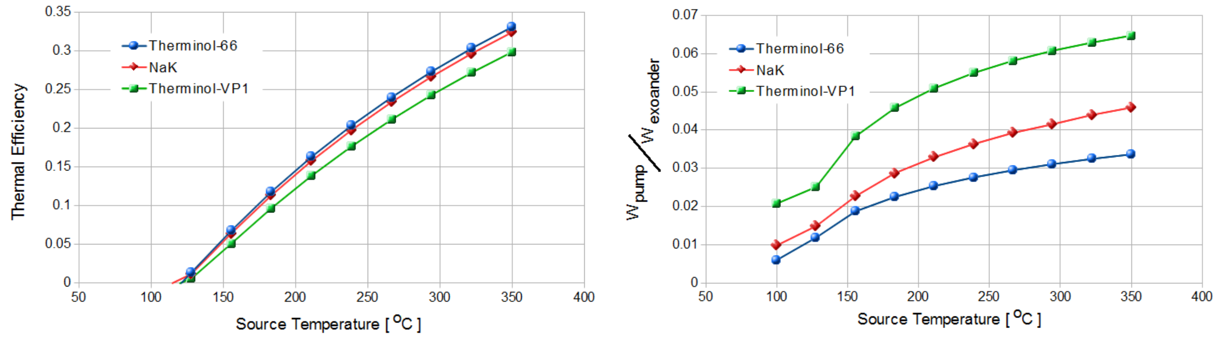

Figure 3: LFEC thermal efficiency (left) and relative pumping losses (right) for various flooding liquids

$$W = \dot{m}v(P_2 - P_1) \qquad P_2 = P_r(P_1) \qquad (3)$$
$$W = \dot{m}vP_1(P_r - 1)$$

The low side pressure has a detrimental influence on the thermal efficiency of the LFEC. However increases in system pressure can improve the power density of the system. The mass flow rate through fixed volume machines can be characterized by a suction volume, the fluid density and operation frequency of the device. This mass flow correlates to the work consumed or produced by the component as shown in equation (4)

$$\dot{m} = \rho V \omega \qquad W = \dot{m}\Delta h \qquad (4)$$

For a fixed volume machine operating at a set speed, an increase in the system density will correspond to an increase in work consumed or produced. With density being proportional to pressure, this means an increase in system pressure leads to an increase in work. For a fixed volume expander and compressor of equal size, the expander will impose the limit on the power output of the LFEC. Due to lower densities at higher temperatures, a lower mass flow rate will pass through the expander than the compressor per revolution. With this in mind, Figure 4 depicts the net power output of the LFEC, as a function of expander suction volume operating at 60 Hz for multiple low side pressures. When designing a LFEC system for an application, a tradeoff must be made between higher conversion efficiencies and increased power density.

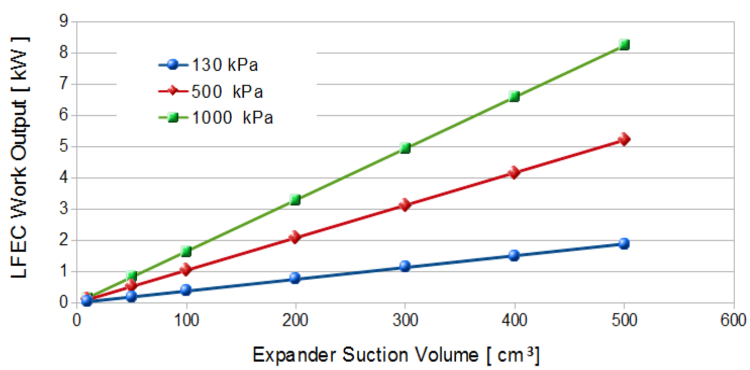

Figure 4: The work output of the LFEC using Therminol-66 for various expander suction volumes and multiple low side pressures. The expander is operating at a speed of 60 Hz.

In Figure 5, the thermal efficiency of the LFEC is plotted against the source temperature for various component efficiencies. The LFEC is extremely sensitive to the efficiency of the rotating components. This is due to the large back-work ratio typical of most gas power cycles. Great effort should be put into designing high efficiency devices compatible with flooding.

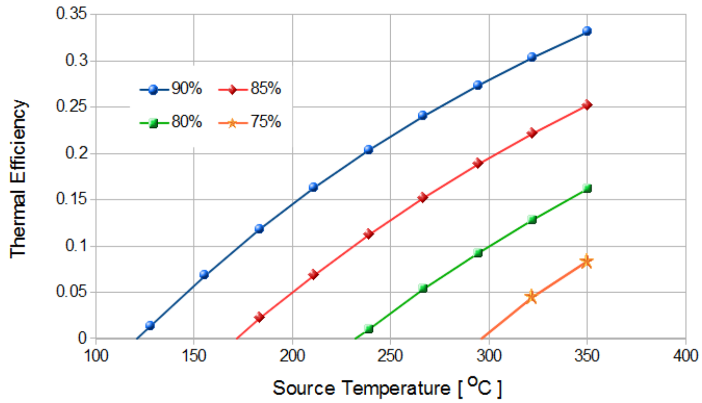

Figure 5: Thermal efficiency versus source temperature for multiple component efficiencies

4. COMPARISON TO ALTERNATIVE CYCLES

4.1 Alternative Cycles Descriptions

Most CSP plants today utilize Rankine cycles for power blocks. Modelling of these cycles was performed in order to understand how the LFEC compares to the status quo. In addition modelling of supercritical CO_2 Brayton cycles was performed. These cycles have been identified as one of the most likely choices to replace Rankine cycles as the power block for CSP plants (U.S. Department of Energy 2012). As such a comparison of the LFEC to supercritical CO_2 cycles was necessary.

The Rankine cycle is a vapor power cycle in which sub-cooled liquid is pressurized by a pump and sent to a boiler to be evaporated. The fluid is then sent through a turbine where work is extracted before being condensed and recycled. Some of the ways to improve the efficiency of these cycles is to utilize reheating and feed-water heating (Cengel and Boles 2008). Reheating is a where the expansion process first begins in a high pressure turbine and is interrupted. The fluid is reheated before continuing to be expanded in a low pressure turbine. Feed-water heating involves diverting some of the high temperature gas from the turbine to preheat the sub-cooled liquid being pumped. A diagram of a Rankine cycle with 1-stage reheat and feed-water heating is shown in figure 6.

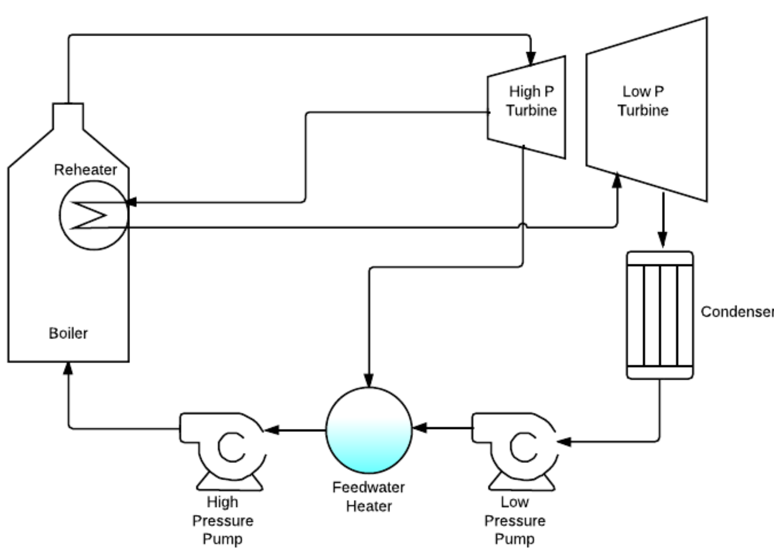

Figure 6: A Rankine cycle with 1 stage reheat and an open feedwater heater.

The ideal Brayton cycle is a gas cycles where gas is isentropically compressed and heated before isentropically expanding. Regeneration can be added between compression and expansion to improve cycle efficiency. The supercritical Brayton cycle differs from conventional Brayton cycles in that it operates in the working fluid's supercritical region. According to Dostál (2009), fluid property changes in the supercritical region reduce the compression work required, which allows for greater net-work output and higher thermal efficiencies. Challenges arise when performing regeneration in the supercritical region. Large changes in fluid properties can lead to pinching within the regenerator. Alternative system arrangements have been explored to overcome this shortcoming. One of the most promising arrangements is the recompression cycle depicted in Figure 7. In this configuration part of the flow is diverted and recompressed without cooling. The diverted flow is then inserted between two regeneration stages.

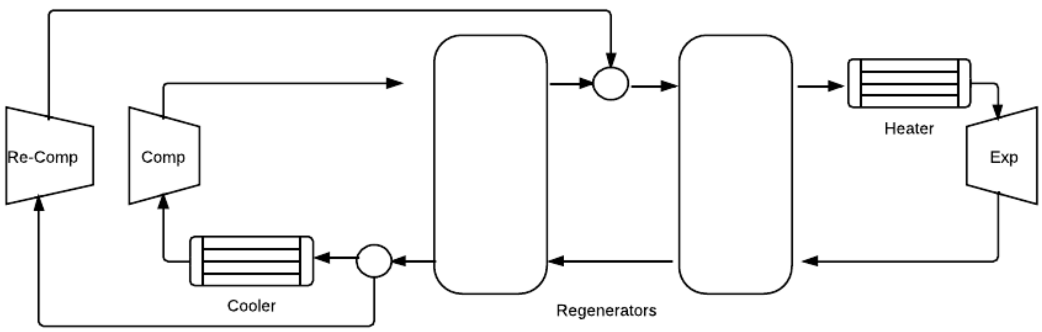

Figure 7: Recompression Brayton cycle. Two regenerators and a recompression stage are used to improve overall regenerator effectiveness and cycle thermal efficiency.

4.2 Model Comparisons

Component based models were developed for the Recompression Supercritical CO_2 Brayton Cycle and the Rankine cycle with reheat and feed-water heating. General parameters used in each model are shown in Table 2. Similar to the LFEC model, EES was used to optimize each system's thermal efficiency at each operating point. The parameters used in the optimization of the Rankine cycle included the overall pressure ratio, the intermediate pressure ratio where reheating and feed-water heating took place, as well as the mass fraction diverted to feed-water heating. For the S-CO2 cycle, the optimization was carried out by varying the system pressure ratio, high side pressure, and mass fraction split for recompression. The regenerator effectiveness was varied in order to maintain a pinch point of 5^{O}C or greater.

Table 2: Model parameters for Recompression Brayton and Rankine Reheat with Feed-water heating models

Parameter	Rankine	Brayton
Working Fluid	Water	Carbon Dioxide
Component efficiency	90%	90%
Heat rejection Temperature	43^{O}C	43^{O}C
Sub-cooling	5 ^{O}C	--
Minimum Regenerator Pinch	--	5 ^{O}C
Max System Pressure	≤ 300 Bar	≤ 300 Bar

A comparison of the performance of LFEC to competing CSP cycles is shown in Figure 8. In this analysis NaK was utilized as the flooding liquid in the LFEC to allow for comparison at temperatures exceeding the range of most thermal oils. At source temperatures above 500^{O}C the LFEC provides greater overall cycle efficiencies than both the Rankine cycle with reheat and feedwater heating and the recompression supercritical CO_2 cycle.

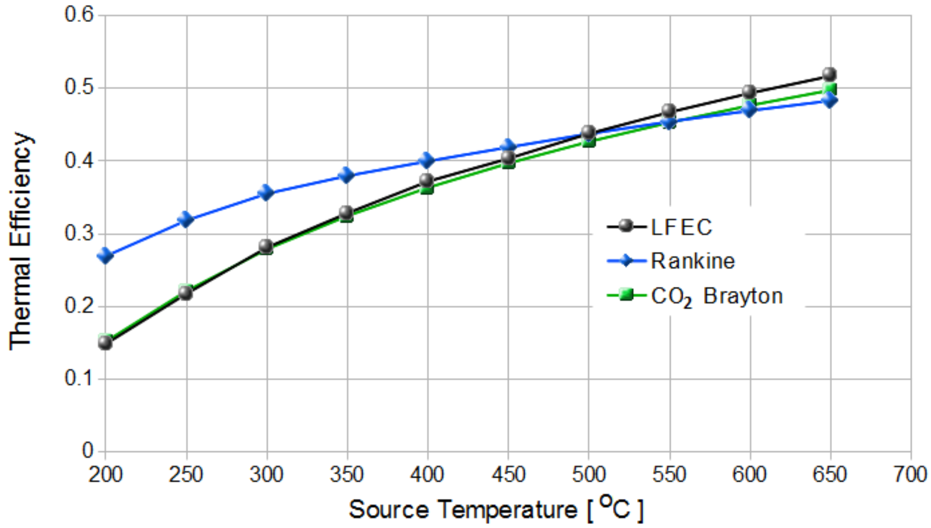

Figure 8: Comparison of LFEC to other cycles of interest to CSP systems

4.3 Integration into CSP Systems

The LFEC possesses other advantages over Rankine and supercritical CO_2 cycles in addition to improved thermal efficiency. One advantage is system simplicity. By directly utilizing the heat transfer fluid (HTF) heated by the solar radiation the LFEC removes the need for an intermediate heat exchanger between the power block and the HTF. The LFEC's high temperature separator can also be utilized for thermal storage. Another advantage of the LFEC is reduced system pressures. Though dependent on the flooding liquid selection and desired power density, the LFEC could feasibly operate below 10 bars. High efficiency Rankine and supercritical Brayton cycles can require pressures in excess of 200 bars. Lower pressures allow for thinner walled surfaces in the LFEC which should lead to increased heat transfer performance with the solar field. These lower pressures also allow the compressor flooding liquid to be pumped directly to a load making the LFEC readily suitable for CHP applications.

The use of fixed volume machines opens up new possibilities for CSP plants utilizing the LFEC. These devices are currently mass produced for the air conditioning and refrigeration industries. By using these devices, high efficiency low cost packaged units can be developed, and a more distributed generation approach to CSP can be pursued. High temperature flooded operation is necessary for improved conversion efficiency of the LFEC. Screw machines have been tested under two phase conditions for geothermal energy recovery (Steidel et al. 1982). In addition scroll machines have been utilized in an Organic Rankine Cycle with liquid flooding (Woodland 2012). Though the temperatures in these applications fall short of those needed for CSP, they give credence to liquid flooding at elevated temperatures.

6. CONCLUSIONS

The Liquid-Flooded Ericsson Cycle has been presented as a high efficiency power cycle for solar thermal power generation. The LFEC can provide competitive conversion efficiencies at a smaller scale than alternative cycles proposed for CSP applications. The thermal efficiency of the LFEC is extremely sensitive to the efficiency of the rotating equipment. Further work must be done to improve the performance of fixed volume machines under flooded conditions. Of particular interest is high temperature operation. Various demonstrations of flooded expansion have been performed; however they operate at temperatures below that needed for CSP applications. The development of devices able to efficiently perform flooded expansion at higher temperatures would make the LFEC an increasingly attractive alternative for CSP and intermediate temperature applications.

NOMENCLATURE

h	specific enthalpy	(kJ/kg)
H	enthalpy	(kJ)
$\dot{m}$	mass flow rate	(kg/s)
m	mass	(kg)
$\dot{Q}$	heat flow rate	(kW)
ε	effectiveness	(-)
W	work	(kW)
P	pressure	(kPa)
T	Temperature	(^{O}C)
V	Volume	(m^3)
ω	frequency	(Hz)
v	specific volume	(m^3/kg)
ρ	density	(kg/m^3)

Subscripts

cool	cool stream
hot	hot stream
r	ratio
regen	regenerator
min	minimum
max	maximum
gas	gaseous working
fluid	
liquid	flooding liquid

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