QGECE Mobile Geothermal Test Plant & ORC Cycle Challenges

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Geothermal energy reserves in Australia have the potential to provide electrical energy for hundreds of years. However, due to the variety of temperatures in geothermal resources a one-size-fits-all approach to surface power infrastructure is not appropriate. Furthermore, the use of traditional steam as a working fluid is rarely a feasible option because resource temperatures lie in the range of 100-200°C. To overcome this, organic fluids with lower boiling points than steam may be utilised as working fluids in organic rankine cycles (ORC) in binary power plants. Due to differences in thermodynamic properties, certain fluids are able to extract more heat from a given resource than others over certain temperature and pressure ranges. This phenomenon enables the tailoring of power cycle infrastructure to best match the geothermal resource through careful selection of the working fluid and turbine design optimisation to yield the optimum overall cycle performance. Here we look at a selection of promising ORC cycles using a range of high-density working fluids operating at sub-, or trans-critical conditions that are being studied by QGECE as potential binary cycle systems; discuss the challenges facing design of ORC cycles and how some of these challenges are being addressed in the QGECE Mobile Geothermal Test Plant.

Keywords: Geothermal energy, Organic Rankine Cycle, Working fluids.

Modelling Binary Power Cycles

In this investigation, the thermodynamic cycle of an ORC was simulated for conditions representative of a geothermal power station. The ORC was modelled as (1) pump work in, (2) heat addition in (i.e. pre-heater, evaporator, superheater), (3) turbine work out, (4) heat rejection out (i.e. pre-cooler, condenser) and (6) regeneration (when the temperatures allow). Figure 1 illustrates the basic layout of an ORC and denotes the state points for calculating thermodynamic properties.

The fluids database employed was the NIST's REFPROP (NIST 2007). REFPROP offers equations of state for 84 pure fluids as well as user defined mixtures. However, only pure fluids were used in this analysis (Mixtures may be the focus of future work).

To allow for ranking results of the various cycles, the critical metric used for comparing fluids and cycles is Brine Consumption (β) (Franco, 2009) defined as follows:

$$\beta = W_{net} / mf_{geo} \text{ (kJ/kg)}$$

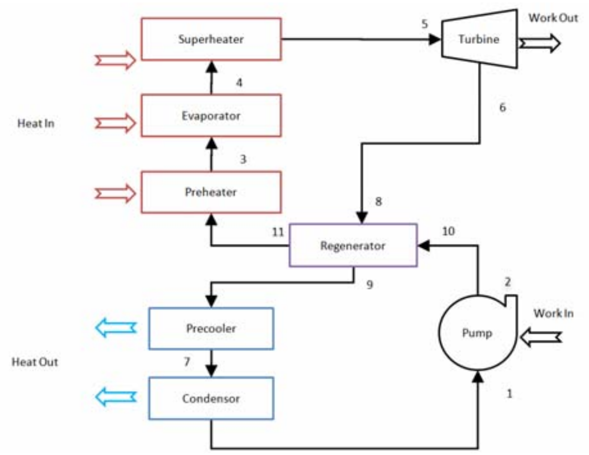

Figure 1: General ORC Layout

Where W_{net} (kW) is the net work produced by the cycle and the mf_{geo} (kg/s) is the mass flow rate of the geothermal brine. Greater β values indicate a greater yield of energy production per unit mass of brine. This can be a good metric for geothermal energy because it focuses on optimising the energy produced for the geothermal brine produced.

The cycle analysis performed indicates that the pinch point in an evaporator has a significant impact on β. This is in agreement with what others have stated previously in other publications (i.e. Saleh 2007). The pinch point is a product of the working fluid's latent heat of evaporation (which is pressure dependent). Minimising pinch point effects will allow the cycle to make more efficient use of the brine flow rate in the evaporator.

In an ideal scenario the brine would cool to the inlet temperature of the working fluid and the working fluid would heat up to the inlet temperature of the brine, transferring all the heat from the brine to the working fluid. However, there will always be a temperature differential between the brine and working fluid because some temperature difference is required to drive heat through the walls of the heat exchanger. The aim then, is to minimise the temperature differential and extract as much heat as possible from the brine flow.

Figure 2 shows an example of a T-s diagram and associated pinch point plot. The cycle represents a subcritical cycle with superheating.

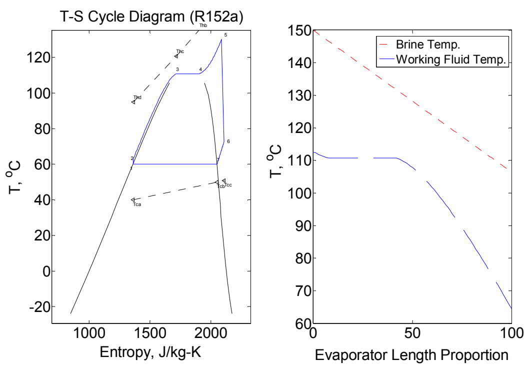

Figure 2: T-s diagram and pinch point plot for R152a (T_{geo} 150°C and T_{amb} 40°C).

Figure 3 shows an example of a T-s diagram and associated pinch point plot. The cycle represents a supercritical cycle. It can be seen that at supercritical conditions the effect of pinch point is gone.

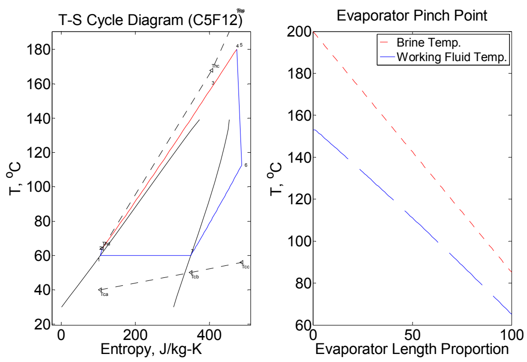

Figure 3: T-s diagram and pinch point plot for C_5F_{12} (T_{geo} – 200°C and T_{amb} 40°C).

Supercritical cycles have the potential to yield efficient cycles because they minimise pinch point effects in the evaporator and there tends to be a large enthalpy differential available across the turbine in the cycle analysis. However, a thorough turbine analysis must be undertaken in conjunction with the cycle analysis to validate the calculated turbine work out from the cycle analysis.

Fluid Performance

Three general categories of geothermal temperature ranges were focused on to see how different fluids performed at different operating conditions. The ranges were labelled as low, mid and high at temperatures of 100, 150 and 200°C, respectively. The ambient temperature was set at 40°C to represent high temperatures that can be seen in central Queensland where our research is focused. For each temperature range the fluids were ranked in ascending order of their calculated β. An abbreviated summary of the results is shown below in Tables 1-3.

An obvious trend in the results tabulated above is that haloalkanes perform well at temperature conditions associated with geothermal resources.

Table 1: Top 5 Fluids (T_{geo} = 100°C)

Fluid	β (kJ/kg)	Evap. Case
C4F10	2.07	Subcritical
C5F12	2.06	Subcritical
RC318	2.04	Subcritical
R227ea	2.04	Subcritical
R236FA	2.03	Subcritical

Table 2: Top 5 Fluids (T_{geo} = 150°C)

Fluid	β (kJ/kg)	Evap. Case
R152a	18.55	Superheated
R134A	18.40	Superheated
RC318	18.28	Superheated
COS	18.14	Superheated
R236FA	17.78	Superheated

Table 3: Top 5 Fluids (T_{geo} = 200°C)

Fluid	β (kJ/kg)	Evap. Case
C5F12	57.91	Supercritical
R236EA	55.67	Supercritical
ISOBUTAN	54.61	Supercritical
R152a	52.06	Supercritical
DME	51.35	Supercritical

Performance maps were also generated for each fluid for a range of temperature conditions (T_{geo} and T_{amb}). This allows for visualisation of how cycle performance can vary with changing inlet brine temperatures (i.e. a geothermal source may cool over its operating life) and ambient air temperature (i.e. for air cooled systems this represents shifts in temperature throughout the day/night and seasonal change). This can be useful in ensuring that the fluid and cycle selected will operate effectively at all anticipated operating conditions. Figure 5 shows an example performance plot for R245fa. The top plot in the figure shows T_{geo} and T_{amb} on the x and y-axes while β is on the z-axis. It is intuitive that when T_{amb} is at a minimum and T_{geo} is at a maximum β would be at its peak value. It is perhaps not so intuitive to see that evaporator pressure associated with the optimum β for a given set of T_{geo} and T_{amb} varies as it does. This can be an important factor in plants performance. If temperatures vary, then so should the pressure (along with other parameters that can be optimised similarly) to achieve the best performance.

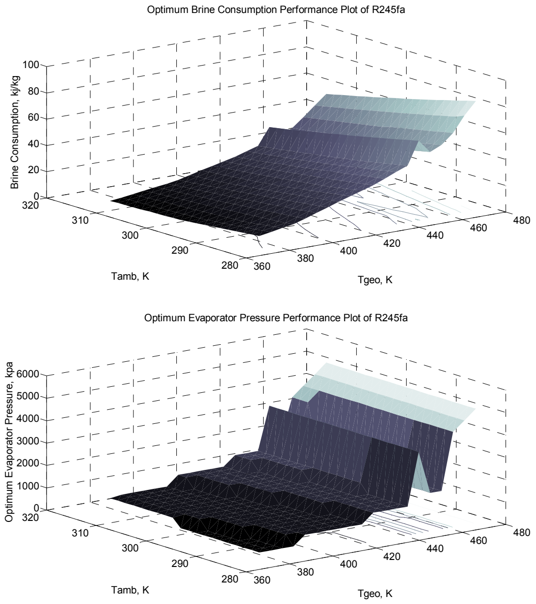

Figure 4: Performance plots for R245fa, optimum brine consumption (top) and associated evaporator pressure (bottom)

Haloalkanes as Working Fluids

Many haloalkanes, especially the hydrofluorocarbons, such as ,1,1,3,3-, Pentafluoropropane (HFC-245fa) and 1,1,1,2-Tetrafluoroethane (HFC-134a), which is in widespread use as a refrigerant, are inflammable, non-toxic and relatively inert. These properties make them highly attractive to use as working fluids in binary power cycles.

One of the drawbacks of these fluids is thermal stability, which, in most cases, is less than the non-halogenated hydrocarbon equivalent and may limit the maximum temperature for which they can be used in power cycles. This is an area of significant uncertainty for ORC technology based on current generation fluids.

Some of the decomposition products can not only cause system performance to degrade but are also toxic and/or strong acids that may negatively impact plant. While some degradation of the cycle fluid to a static level may be tolerable in certain situations, gross scale degradation over time of the working fluid is not acceptable.

While there have been a number of studies (Angelino, 2003; Calderazzi, 1997) looking at the stability of these fluids, existing data does not necessarily agree on exact degradation temperatures and have, in general, looked only at the stability when in contact with stainless steel, which has negligible catalytic interaction. However, in real-world applications the working fluid may come into contact with a number of different materials, all of which may interact differently with the working fluid and may further reduce the reported degradation temperature. Further effects, including atmospheric contamination (e.g. the presence of small amounts of water, which may accelerate decomposition) have not been thoroughly investigated to the best of our knowledge.

This is of concern when designing a plant as the presence of materials that may act as catalysts for degradation must be avoided in all parts of the system that come into contact with the working fluid. Even common materials used in heat exchangers may be cause for concern.

Optimising the Operating Pressure

Not only do certain fluids perform better than others at certain temperatures, but there exists an optimum pressure for cycle performance.

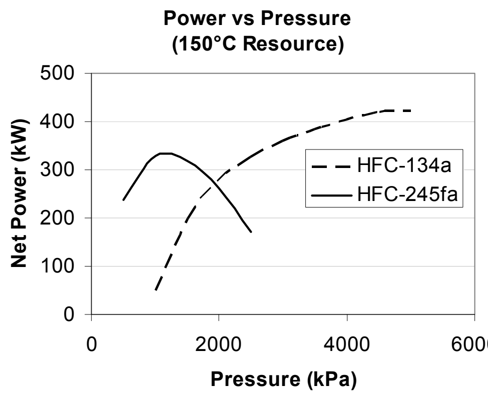

Figure 5: Optimum cycle pressures at 150°C for HFC-134a and HFC-245fa.

The general assumption that higher pressure directly translates to higher work output does not necessarily hold true at pressures both below and above the critical pressure, depending on the fluid in question. Figure 5 shows the calculated power output over a range of pressures for HFC-134a and HFC-245fa at operating temperatures of 150°C. As can be seen, at this temperature the optimum system pressure for these two fluids is different and produces significantly different net power outputs.

Optimising the Turbine

Working fluid properties, resource temperature, flow rate and condensing pressure are all variables that dictate turbine design. In most instances, the goal is to generate the highest output power possible. Therefore design optimisation centres around generating the highest efficiency turbine. Generally, this results in turbine designs that need to operate at high rotational speeds that are not suitable for direct coupling to grid synchronous generators. QGECE is focussing on optimising turbines that have operational speeds of 24,000 RPM (400 Hz). This results in high operating efficiencies and is compatible with existing power electronics, such as that found in aircraft. To date, current QGECE preliminary turbine design has not indicated dramatic differences in turbine efficiencies for various ORC cycles operating with pressure ratios of between 2 and 6.

Optimising the Cycle

So far we have touched on a number of considerations of various key cycle components including the working fluid, system operating pressure and turbine design. When combined, a different picture may begin to emerge as to the composition of elements that yields optimum power output for a given resource temperature. For instance, depending on the design conditions assumed in the thermodynamic cycle analysis, the pressure ratio calculated that gives an optimum theoretical cycle performance may result in a suboptimal turbine efficiency, which may affect the initial ranking of working fluid selection.

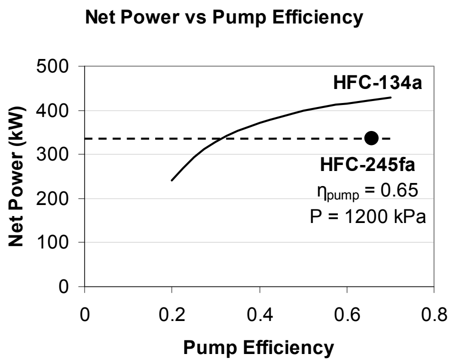

Figure 6: Effect of η_{pump} on net power.

Furthermore, variations in efficiencies of other components in the system are often neglected in theoretical studies for ease of comparison, but can have a large impact on overall system performance. For instance, the benefits of trans- and supercritical cycles can be harnessed only if high performance pumps or compressors exist for the required conditions, otherwise a subcritical cycle may become increasingly attractive due to lower pump work and reduced operating pressures. Figure 6 shows the impact on net power for a supercritical HFC-134a cycle operating at 5 MPa compared to an optimised subcritical HFC-245fa cycle operating at 1.2 MPa at the same temperature.

QGECE Mobile Test Plant (Terragen)

The Terragen Project is a QGECE initiative to develop a modular portable transcritical power plant able to generate approx. 75 kW of power from geothermal or waste heat sources. One of the primary goals is to demonstrate that useful amounts of energy can be produced even from low-grade resources using transcritical fluids.

Terragen consists of three containerised modules: a control module, power-plant module and an air condenser module. The system is being designed around two working fluids HFC-134a and HFC-245fa using oil-free technologies.

Terragen will be a real-world demonstration and validation of cycles and technologies being developed at QGECE and will primarily be an experimental rig based at The University of Queensland's rural Pinjarra campus. The portable nature of Terragen means that it will also be available for companies to carry out well-testing and help prove the electricity-generation capability of resources to assist with attracting public and private sector funding.

Terragen is currently under development in collaboration with our project partner, Verdicorp, and is expected to be completed mid-late 2011.

Conclusions

The general assumption that higher pressure directly translates to higher work output does not necessarily hold true at pressures both below and above the critical pressure, depending on the fluid in question. Figure 5 above shows the calculated power output over a range of pressures for HFC-134a and HFC-245fa at operating temperatures of 150°C.

In developing an ORC that generates optimum cycle power output from a given resource there are a number of critical considerations including, but not limited to, selection of best-suited fluid for operating temperature; selecting optimised operating pressures for chosen fluid; optimised turbine design and selection of auxiliary cycle components that complement these major cycle elements.

Future work will work towards verifying the predicted performances experimentally both in the lab at small power scales and at larger scale using the QGECE Mobile Plant. Furthermore, future work will address the life cycle analysis of implementing various sub- and transcritical cycles to verify that the cycles that give the best performance theoretically still out-perform the other cycles on an economic and feasibility basis.

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