How to Increase Geothermal Power Conversion Efficiencies

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Geothermal power plants in dry regions typically use air cooling and consequently suffer from reduced efficiencies during hot days. In this paper, it will be demonstrated it may be possible to use solar boosting to maintain the geothermal plant power generation in such instances. It will be shown that commercial feasibility of solar boosting is improved when the cycle fluid is heated over a variable temperature range instead of the steam or organic Rankine cycles with fixed evaporation points. Results with supercritical CO_2 cycles will be compared against more conventional alternatives.

Keywords: power conversion; supercritical cycles; solar energy; hybrid plants; hot rock geothermal.

Introduction

Two factors prevent widespread adoption of HFR (Hot Fractured Rock) geothermal power in Australia:

- Compared to other renewables, there is a higher technical risk in HFR projects, namely in locating, establishing and exploiting a reservoir. This risk will be constrained with progress but will never disappear since each new prospect will be unique.
- Compared to coal- or gas-fired plants, geothermal plants need to dump several times more waste heat per MW of electricity generated. Without easy access to water, this can be a problem.

Higher potential rewards make risks more affordable. The reward from HFR investment is the electricity generation. If this reward can be increased, then higher risks would be acceptable to the investors.

The electricity generation from a given geothermal fluid source depends on:

- the fraction of the heat extracted from the geothermal fluid; and
- the efficiency of converting the extracted heat to electricity.

Let us start with the second one, a.k.a. the thermal efficiency. The thermal efficiency for a power conversion cycle is defined as the net turbine shaft power divided by rate of heat input into the cycle working fluid. The theoretical limit on thermal efficiency is the efficiency of the Carnot cycle, which represents ideal power conversion conditions. The actual efficiencies are usually much lower than the theoretical efficiency due to unavoidable losses. A good indicator of the maturity of a technology is what fraction of its Carnot efficiency it is able to deliver in actual operations.

In Figure 1, we plot the fraction of the corresponding Carnot efficiencies realised by operating geothermal, nuclear, coal, and combined-cycle gas turbine plants. The geothermal plant efficiencies are for binary plants calculated from data provided in Tester (2006) and the other plant data are from Willson (2007).

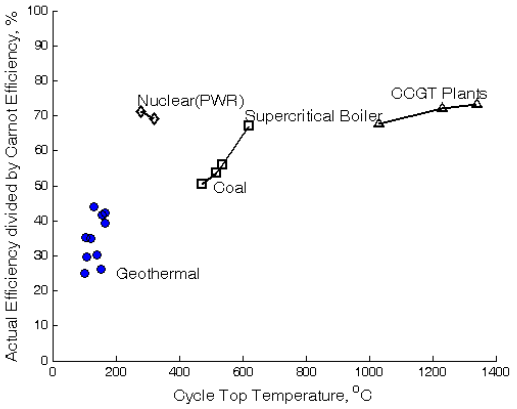

Figure 1: Fraction of the theoretical limit realised by different power generation technologies.

The important message from Figure 1 is that less than 40% of the ideal efficiency is realised in actual geothermal practice and the ratio is as low as 30% for low reservoir or high ambient temperatures. In contrast, any other modern power technology is able to enjoy around 70% of its ideal efficiency limit. Clearly, the geothermal energy practice has room to improve.

A significance source for efficiency loss in geothermal power plants is the irreversibility in the heat exchangers, e.g. see Demuth(1979), Larjola(1996), Vargas(2000), Chen(2006), Bronicki(2008).

Such irreversibilities can be significantly reduced by continuously matching the cycle fluid temperature against the temperature of the geothermal fluid during the heat exchange process. This is not possible in a conventional Rankine-cycle plant but easy in a supercritical cycle.

Case Study Definition

The analysis will be based on conditions that can be found in a typical Cooper basin HFR geothermal reservoir. We are assuming that hot brine is produced from a number of production wells at a temperature of 250°C at the rate of 500 l/s. The ambient air temperatures change from

about 0 °C during a cold winter night to 45 °C on a hot summer day.

We will consider two power plants to exploit this resource. One will be based on a supercritical CO_2 cycle and the other on a steam cycle. The steam cycle is conventional technology although it is usually employed at higher temperatures. The supercritical CO_2 cycle is a new technology development being pursued by the Queensland Geothermal Energy Centre of Excellence.

Supercritical Cycle vs Conventional Technology

Figure 2 shows the supercritical CO_2 diagram on temperature-entropy coordinates. A regenerator is used to recover some of the heat in the turbine exhaust stream.

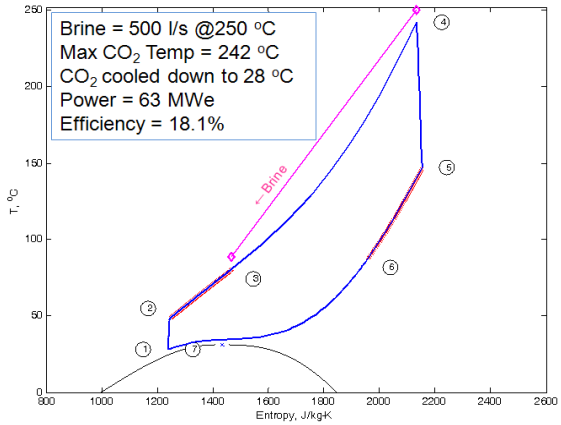

Figure 2. The supercritical CO_2 cycle

The case study temperatures are too high for an organic rankine cycle. The conventional technology for this temperature range is offered by a steam Rankine cycle. This is shown in Figure 3.

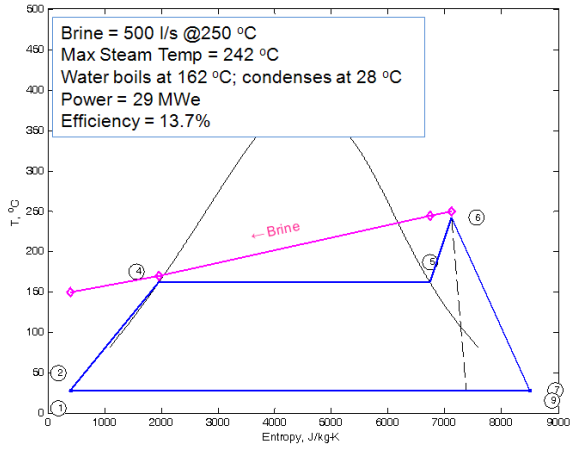

Figure 3. Conventional steam cycle

Cycle computations indicate that a power plant based on the supercritical CO_2 cycle has the capacity to generate 63 MWe at an efficiency of 18.1%. In comparison, the proven technology could only generate 29 MWe from the same reservoir and have an efficiency of 13.7%.

In other words, the supercritical CO_2 plant produces than more than twice the amount for the same resource. The performance varies through the year with the ambient temperature and the supercritical plant is more sensitive to the ambient temperature than the steam plant. Nevertheless, the expected annular electricity generation by the supercritical plant is 50% higher than that by the steam plant for the same geothermal resource and the same climate. The full comparison between the supercritical plant and the conventional technology is shown in Table 1.

Table 1. Comparison of supercritical CO_2 cycle and conventional plant performance

	CO_2 cycle	Steam cycle
Brine temperature, °C	250	250
Brine flow rate, kg/s	500	500
Brine return temperature, °C	89	150
Design-point power generation, MWe	63	29
Annual generation, GWh	401	256
Waste heat, MWth/MWe	4.5	6.4
Wet cooling tower water use, kg/kWh	8.0	8.2

Both plants operate on the same geothermal resource with the same subsurface investment. At an electricity sale price of 10¢/kWh, the difference in annual revenue would be about A$15m.

The water usage in Table 1 is provided only for comparison purposes. Otherwise, the analysis in this section assumes conventional dry cooling tower technologies with a heat exchanger approach temperature difference of 8oC. On hot days, this reduces the plant output significantly. Using innovative cooling technologies as explained in the next section, this vulnerability to high ambient temperatures can be minimised.

Dry Cooling Tower Technologies

Whether one uses new technology or established technology, for each MW generated several multiples of that amount must be dumped at waste heat. A more efficient plant would dump a lesser amount per MWe but large amounts heat must be dumped for either cycle.

In many geothermal plant locations, water is scarce and air cooling is the only option. Air cooling can be done by using fans or by using natural draft through a cooling tower. The fan-driven systems can be built quickly and at relatively low cost but their operating costs are higher due to their higher maintenance

requirements and the parasitic losses associated with running the fans.

The Queensland Geothermal Energy Centre of Excellence will do system studies, develop advanced heat exchanger technologies, and explore innovative systems towards better natural draft cooling towers. One of the options considered by the Centre is a low-cost air-lift cooling tower as depicted in Figure 6.

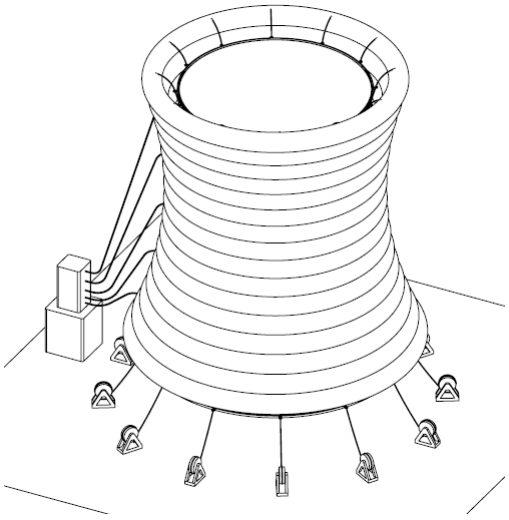

Figure 4. Innovative cooling tower design

Figure 4 shows an innovative cooling tower concept being investigated by the Queensland Geothermal Energy Centre of Excellence.

The tower is built as a flexible shroud and is held in place in tension by the buoyancy force acting on the toroidal rings filled with lighter-than-air gas.

There are a few issues associated with this concept but the Centre is expecting to be ready to build a prototype by mid-2010.

The motivation for the air-lift cooling tower shown in Figure 4 is to enable construction of very tall cooling towers at an acceptable cost.

Taller towers would increase the suction air velocity and the heat transfer at the heat exchangers and they also would enjoy lower tower exit temperatures.

Another system innovation under consideration targets the exploitation of clear and dry nighttime skies typically found in the Australian outback.

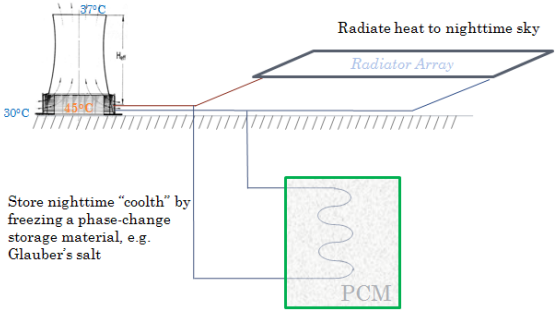

Figure 5. Nocturnal cooling for power plants

The system depicted in Figure 7, aims to cool a stored medium by using radiative coolers at night.

The night-time sky temperature is about 0 °C through the year in most of Central Australia.

Either sensible or latent storage can be used to extend nighttime cooling through the day. The required investment is smaller for a supercritical cycle where the first ΔT of cooling can be done by air (e.g. from 90 °C to 40°C) and the second ΔT by the stored coolth (e.g. from 40°C down to 20°C).

Supercritical Rankine Cycle

If a geothermal plant has access to cold water or if some of the cooling technologies of the previous section can be judiciously implemented, it might be possible to design a plant at an even higher efficiency. In a supercritical Rankine cycle, CO_2 would condense at a temperature below 30 °C and it would then be heated to supercritical temperatures and expanded as a supercritical gas. The temperature-entropy diagram for a supercritical CO_2 Rankine cycle is shown in Figure 6.

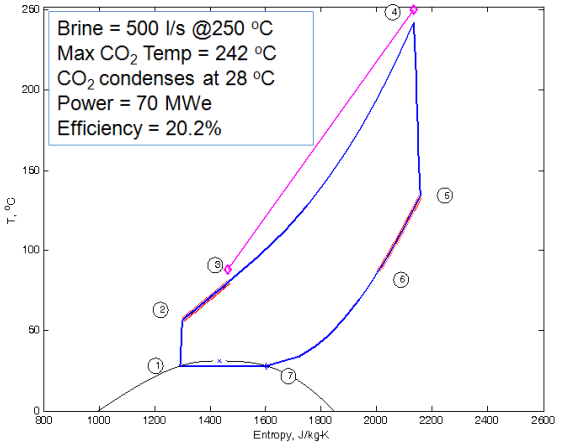

Figure 6. Supercritical CO_2 Rankine Cycle

The cycle shown would deliver even higher power. Since the critical point for CO_2 is about 30 °C, this plant would require access to a cooling medium well below 30 °C.

That is why a supercritical Rankine cycle may not be feasible for most Australian geothermal plant locations unless it is combined with other innovative cooling options as described elsewhere in this paper.

Geothermal + Solar Hybrid Plants

Another interesting opportunity with supercritical cycles is to use solar heat to maintain the plant output on hot days.

For example, by adding solar boosting to the plant of Figure 2, one can maintain the design output at ambient temperatures as high as 45°C. The supercritical cycle with solar boosting under these conditions is shown in Figure 7.

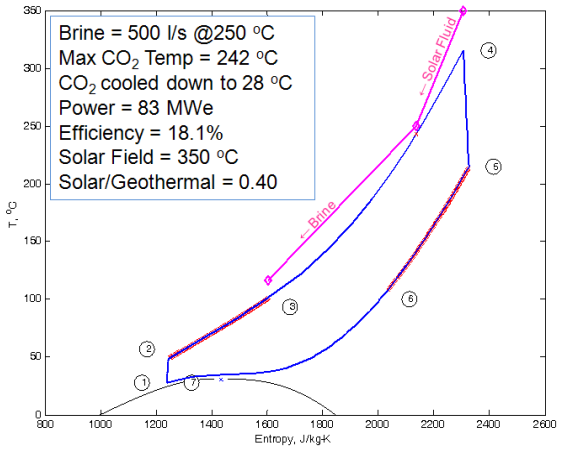

Figure 7. Supercritical CO_2 Brayton cycle with solar boosting

It is difficult to make solar boosting economically feasible with steam plants. This is because most of the heat added to the Rankine cycle is latent heat at the saturation temperature corresponding to the turbine design inlet pressure. It is not possible to significantly shift this temperature upwards without changing the turbine inlet pressure. Changing the pressure requires a separate turbine. Therefore, solar boosting of a geothermal plant based on a steam cycle requires two turbines: one for geothermal-only operation and the other for geothermal + solar. Even then, the optimum operating point would be elusive because of variable solar incidence and the inability of the plant to optimally track such variations. In a supercritical cycle, the turbine inlet temperature and the pressure are not linked and the solar heat can be added to the cycle fluid on the same pressure line as shown in Figure 7.

Supercritical CO_2 Geothermal Siphon

The use of CO_2 as a geothermal heat exchange fluid has been proposed by Brown (2004) and Pruess (2006). Gurgenci (2008) and Atrens (2008) and Atrens (2009) expanded the concept to include the power conversion using a supercritical CO_2 cycle. A supercritical CO_2 cycle achieves higher efficiencies but even then hardly catches up to the maturity of technology available to coal- and gas-fired power plants. For example, the supercritical CO_2 Rankine cycle of Figure 6 has a thermal efficiency of 20.2%, which is 49% of its theoretical limit. This is much better than the second law efficiency of 33% for the steam cycle of Figure 3 but still below the 60-70% enjoyed by coal and gas plants as shown in Figure 1.

By using a supercritical cycle, the heat exchanger irreversibility is reduced but not eliminated. The heat exchanger irreversibilities can only be eliminated when we do not use heat exchangers. This is possible if we use the same CO_2 for geothermal heat exchange in the reservoir and expand it through the turbine when it comes to the surface and send it back to the reservoir after cooling it. The cold CO_2 would sink in the injection well and the hot CO_2 would rise in the production well. No significant compression input or downhole pumping would be necessary to drive the system described in Figure 8.

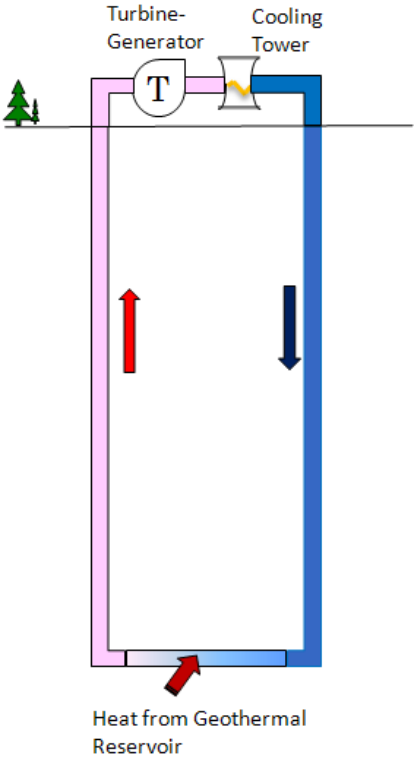

Figure 8. Operation of the supercritical CO_2 geothermal siphon

This is a new concept where supercritical CO_2 extracts reservoir heat, rises to the surface and drives a turbine, and then is cooled and sent back underground to close the cycle.

The concept offers the following intrinsic advantages over the alternatives:

- Driven by the buoyancy of the hot fluid, it does not need a submersible pump
- Removing the binary plant heat exchanger increases efficiency and lowers capital costs
- Better geothermal heat extraction enables larger well separation and longer plant life

Access to large quantities of CO_2 is essential, first, to start the reservoir and, then, possibly to make up for underground capture. The cost of such access could be defrayed by the CO_2 sequestration benefits.

Conclusions

The Queensland Geothermal Energy Centre of Excellence (QGECE) of The University of Queensland is working towards the following research outputs in the next two years:

- Supercritical CO_2 turbines for high-grade geothermal resources and solar/geothermal hybrids

- Better dry cooling technologies for geothermal and solar thermal power plants in arid regions
- Delivery of these outputs will quicken the large-scale adoption of HFR geothermal energy in Australia and around the globe.

In this paper, we compare the proposed technologies to present alternatives and identify and quantify the potential benefits from such research.

Comparing geothermal power against more mature technologies such as nuclear, coal power plants, and gas turbines, we first identify a clear potential to increase geothermal power conversion efficiencies by at least 50%. Incremental improvements cannot realise such a potential. A fundamentally new approach is needed. Supercritical cycles offer such a fundamentally new alternative.

A supercritical CO_2 cycle is the superior alternative at geothermal fluid temperatures above 200 ^oC. These temperatures are too hot for organic fluids but not hot enough for steam cycles. At 250 ^oC, for example, we demonstrate that a supercritical cycle would double the power available from conventional technology. For a geothermal plant based on a 500 l/s hot brine resource, this means and additional revenue of $15m per year at an electricity sale price of 10¢/kWh.

Most of the components in a supercritical CO_2 cycle are off-the-shelf technology except for the turbine. To deliver the missing link, QGECE is aiming to demonstrate a 5-kW prototype demonstrated in the laboratory by mid-2011 and develop the funding and the partnership for a 1-MWe demonstration project by mid-2013.

Even then, HFR geothermal plants may still be unviable in hot and arid regions without better dry cooling technologies. QGECE is pursuing advances in this area through incremental research and system innovations. Some of the target innovations are described in this paper.

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