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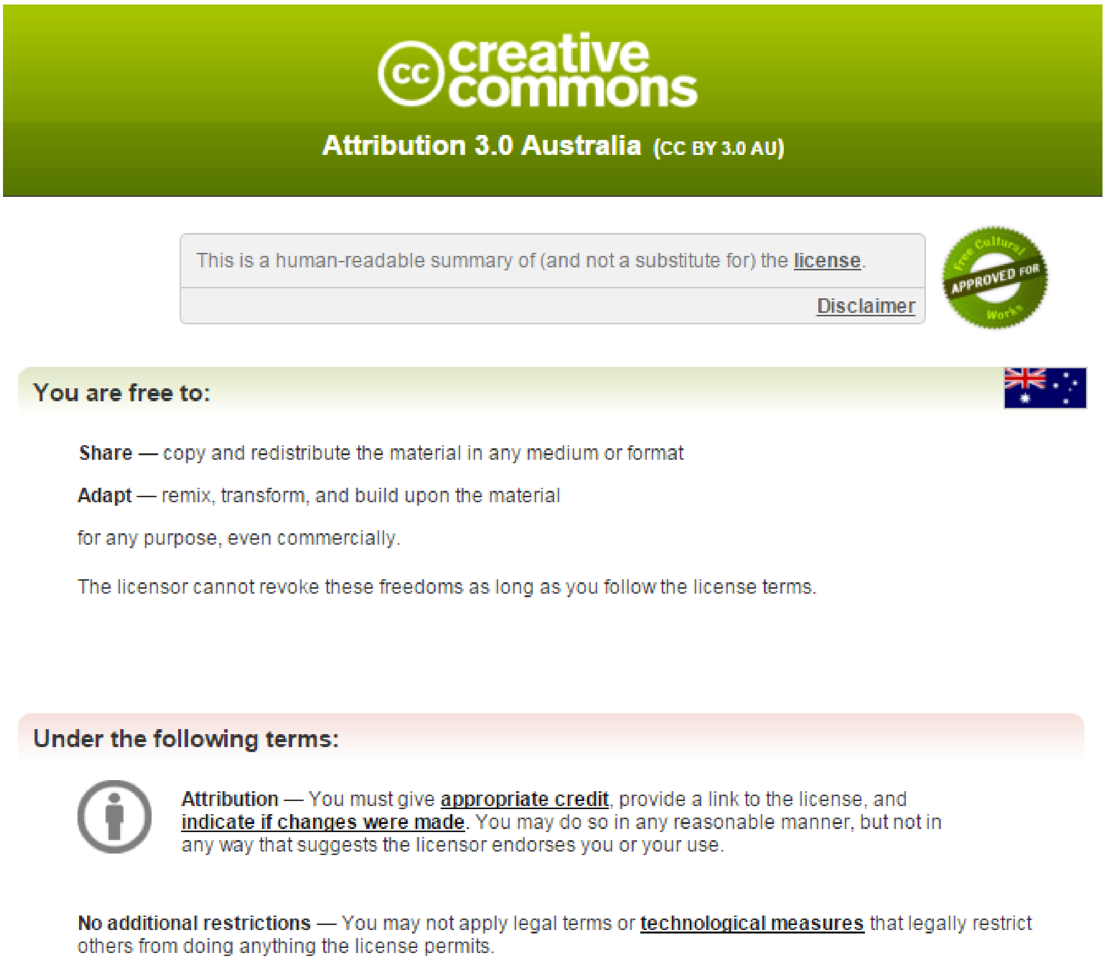

Performance of air-cooled organic Rankine cycle plants using temperature distributions from arid parts of South Australia

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Abstract

Air-cooling is necessary for geothermal plays in dry areas and ambient air temperature significantly affects the power output of air-cooled thermal power plants. Hence, a method for determining the effect of ambient air temperature on subcritical and supercritical, air-cooled binary Rankine cycles using moderate temperature geothermal fluid and various working fluids is presented. Part of this method, includes a method for maximizing working fluid flow from a supercritical heat exchanger. In the example presented isobutane is used as the working fluid, while the geothermal fluid temperature and flowrate are set at 150°C and 126kg/s. Results of this analysis show that for every 14°C increase in ambient air temperature, above the ambient temperature used for design purposes, there is ~20% loss in brine efficiency; while conversely, there is no gain in brine efficiency for any drop in ambient air temperature below the ambient air temperature used for design purposes. Using the ambient air temperature distribution from Leigh Creek, Australia, this analysis shows that an optimally designed plant produces 6% more energy annually than a plant designed using the mean ambient temperature.

Introduction

Air-cooling is necessary for geothermal plays in the South Australian desert and other dry areas. Ambient air temperature significantly affects the power output of air-cooled thermal power plants, and so a method for quantifying and predicting this effect is needed. This paper presents a method for determining the effect of ambient air temperature on subcritical and supercritical, air-cooled binary Rankine cycle plants. This model is built using basic thermodynamic principals only and does not use or rely on industry standard models such as GETEM or ASPEN. This significantly reduces the number of inherent assumptions and the subsequent complexity, making cause and effect clearer.

Since each site can have only one plant, it can only be optimally designed for one ambient air temperature. Therefore, the plant must run in off-design conditions when the current ambient air temperature is higher or lower than the design ambient temperature. Assuming a geothermal fluid temperature of 150°C, the results of this analysis show that for every 1°C increase in immediate ambient air temperature, above the design ambient temperature, there is ~1.5% loss in brine efficiency. While conversely, there is no gain in brine efficiency if the current ambient air temperature drops below the design ambient air temperature.

Using the ambient air temperature distribution from Leigh Creek, South Australia, further analysis shows that an optimally designed plant produces 6% more energy, annually, than a plant designed for the mean ambient temperature. Similar results are obtained for geothermal fluid temperatures up to 250°C, using temperature distributions from Moomba, Roxby Downs and the Coonawarra.

Method

The majority of Australia's 366 existing geothermal exploration licences are located in arid to semi-arid areas of the continent, targeting relatively low enthalpy EGS and HSA targets. In this context, it is likely that binary Rankine cycles and air-cooling will be the most viable technologies for electricity production from many projects. Hence, we chose, in this paper, to model an air-cooled binary Rankine cycle plant.

A binary Rankine cycle plant has two separate circulating fluids: the *geothermal fluid* which brings the heat from deep in the earth to the surface, and the *working fluid* which takes heat from the geothermal fluid and uses this heat to generate electricity (see Figure 1).

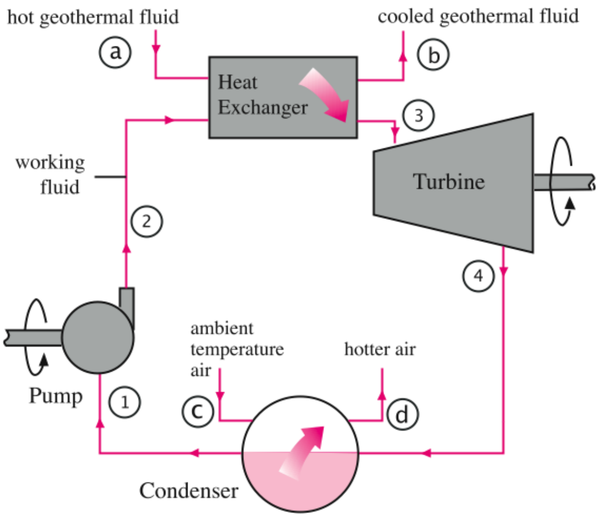


Figure 1: *Schematic for an air-cooled binary Rankine cycle*

Although not commonly mentioned, all Rankine cycles have another fluid, the *cooling fluid*; this is the fluid which removes heat from the vaporized working fluid, allowing it to condense and then be pumped back up to pressure. Generally, this cooling fluid is water because it has excellent thermodynamic properties for cooling, it is stable, abundant and cheap (which explains why 99% of the power plants in the USA use water cooling [5, p. 12]). However, where water is scarce, ambient air is used for cooling because it is also stable, abundant and cheap (although its thermodynamic properties, for cooling purposes, are not as good as water).

The working fluid in a Rankine cycle goes through four separate *processes*, changing the fluid into four different *states*. At State 1 the working fluid is a low pressure, low temperature saturated liquid, it is then pumped up to high pressure liquid (State 2), and then heated to become a high pressure vapor (State 3). Pressure and temperature, of the working fluid, drop across the turbine (to produce mechanical energy) to leave a low temperature, low pressure vapor in State 4. This vapor is then condensed to become the low pressure, low temperature saturated liquid of State 1, and the cycle starts again.

An *ideal* Rankine cycle assumes that the pump and the turbine operate isentropically, and that the condenser and the heat exchanger operate at constant pressure. Determining the power output from an ideal Rankine cycle is well known and widely covered in textbooks [1, 9, 2] so we will not go into it in detail here (for more information see paper ‘Building a model to investigate the effect of varying ambient air temperature on air-cooled organic Rankine cycle plant performance’ also presented at AGEC2012). Simply, if the following are known:

1. temperature of the saturated liquid at State 1,
2. temperature and pressure of the vapor at State 3,
3. working fluid mass flowrate,

the net-power generated by the ideal Rankine cycle can be determined.

Results

For a given set of plant conditions ($m^{GThF}, T_a^{GThF}, p_b^{GThF}$, working fluid and $T_{\text{design amb}}$) and an ambient temperature distribution it is possible to determine the energy output of an air-cooled binary Rankine cycle.

First, we examined the effect of ambient air temperature on brine efficiency for four different geothermal fluid temperatures (150°C, 175°C, 200°C, 225°C and 250°C). These results show the effect of an ambient temperature on a given day; so, on any site on any day, if you have these design conditions, this is the brine efficiency you can expect.

These results (see Figure 2), show that ambient air temperature has a significant impact on the power output of air-cooled binary Rankine cycle plants, for thermal fluid temperatures of 150°C - 225°C. More specifically, according to our modeling, these plants lose around 10-15% brine efficiency for every 10°C increase in actual ambient air temperature, above the design ambient air temperature. Further, when the actual ambient air temperature is colder than the design ambient air temperature, there is no increase in brine efficiency.

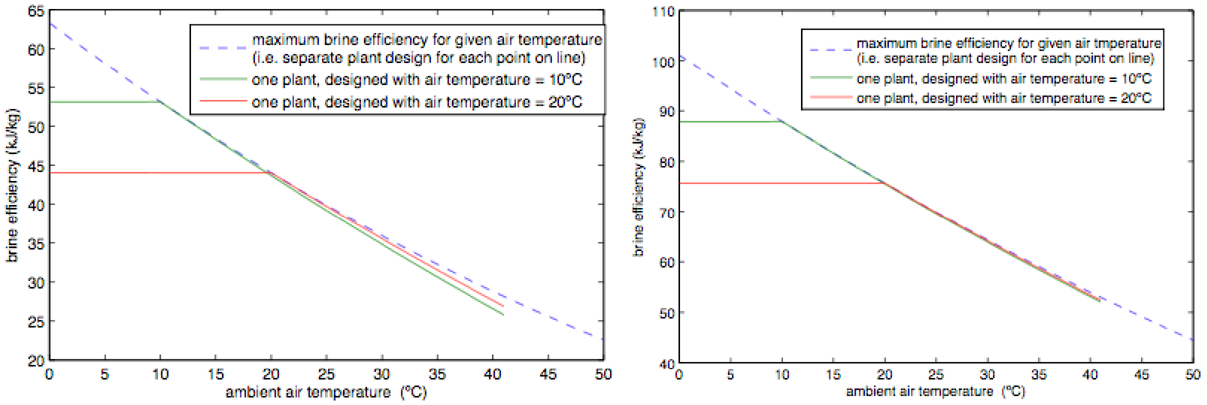
Each graph in Figure 2 shows, what we call here the `maximum line', the maximum brine efficiency for all ambient air temperatures (i.e. this line assumes a new plant was designed for each point on this line). The maximum line is compared, in this Figure, to two individual plant designs, with design ambient air temperatures of 10°C and 20°C. Clearly, the brine efficiency for a single plant, will meet the `optimal line' at the design ambient air temperature. From Figure 7, it is also easy to see that a plant loses significantly more, in comparison to the optimal line, at temperatures which are colder than the design ambient air temperature, than it does from temperatures which are hotter than this temperature.

However, Figure 2 doesn't answer the question, `What is the best plant design for a specific temperature distribution?' Most air-cooled binary plants are designed at the mean ambient temperature. Looking at Figure 7 it is difficult, if not impossible, to decide if this is the best choice for your site. To be able to quantify the effect of ambient temperature at a given site, it is necessary to consider the temperature distribution for that site.

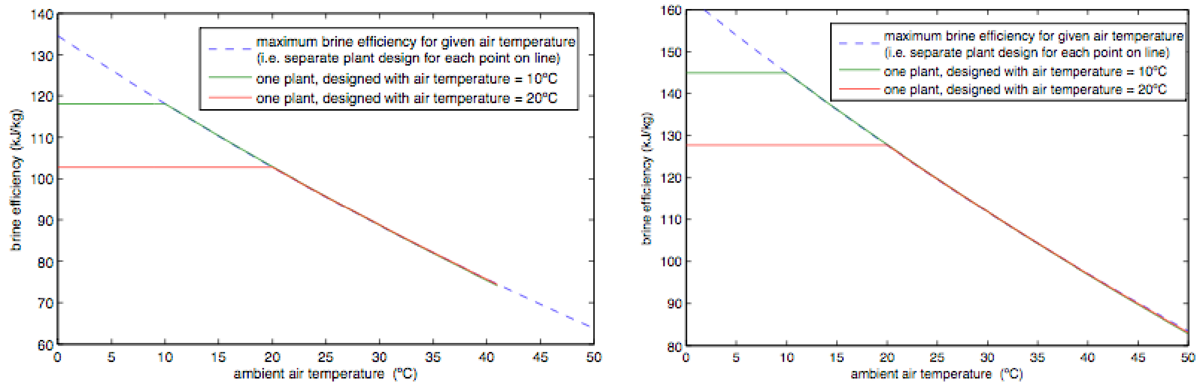
From the Australian Bureau of Meteorology we obtained half-hourly temperature data from three sites in South Australia: Leigh Creek, Moomba and the Coonawarra; and used this data to calculate a yearly time average of the actual brine efficiency for a range of design ambient temperatures. The *yearly time average brine efficiency* is the sum of the actual brine efficiencies for each temperature in a calendar year multiplied by the time at that temperature divided by the time in a year. So, for a plant that under ideal conditions (i.e. you had the design ambient air temperature every moment of every day of the year) has a brine efficiency of 120kJ/kg, once you consider the actual ambient temperature distribution for that site the plant may only produce on *average* 116kJ/kg.

The yearly time averaged brine efficiency results for Moomba are shown in Figure 3, the results for Leigh Creek are shown in Figure 4, and the results for the Coonawarra are shown in Figure 5. These results show that yearly time averaged brine efficiency plateaus or even drops off at colder design ambient temperatures, while it decreases sharply with hotter design ambient temperatures. This sharp decrease begins around 5-10°C colder than the site’s mean temperature.

Many air-cooled binary Rankine cycle plants choose the mean ambient air temperature (at their site) to use as their design ambient air temperature. Our results show that building a plant using a design ambient air temperature of ~10°C colder than mean yearly air temperature would increase the yearly time averaged brine efficiency by 5-8%.



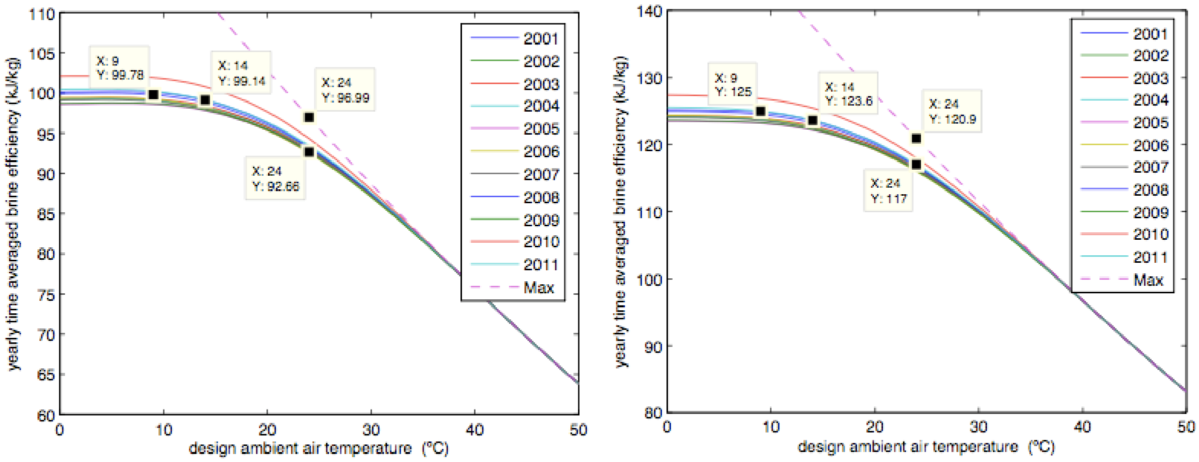
(a) Theoretical data for T_a^{GThF}= 150°C (b) Theoretical data for T_a^{GThF}= 175°C



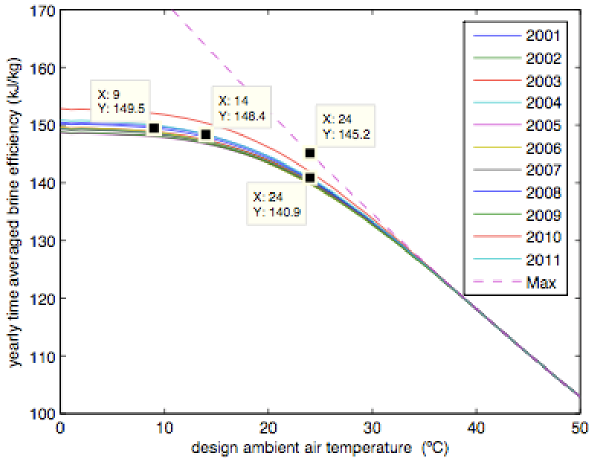
(c) Theoretical data for T_a^{GThF}= 200°C (d) Theoretical data for T_a^{GThF}= 225°C

Figure 2: *Theoretical data for various geothermal fluid temperatures*

- A blue dashed line for maximum brine efficiency for the given air temperature (i.e. a separate plant design for each point on the line). This line is roughly linear and brine efficiency descends with increasing air temperature, for all geothermal fluid temperature options.
- A green line representing one plant designed with an air temperature of 10°C. This line is horizontal from the left of the graph, until it meets the maximum brine efficiency line. It then fairly closely follows the maximum brine efficiency line. For plots a and b, however it drops increasingly below this line with increasing ambient temperature.
- A red line representing one plant designed with an air temperature of 20°C. This line follows the same curve as the green line above. However, since it starts on the left at a lower point, it is always lower than the green line until it meets the maximum brine efficiency line, there after it is always above the green line (since it has started is movement away from the blue line at a later point that then green line).]

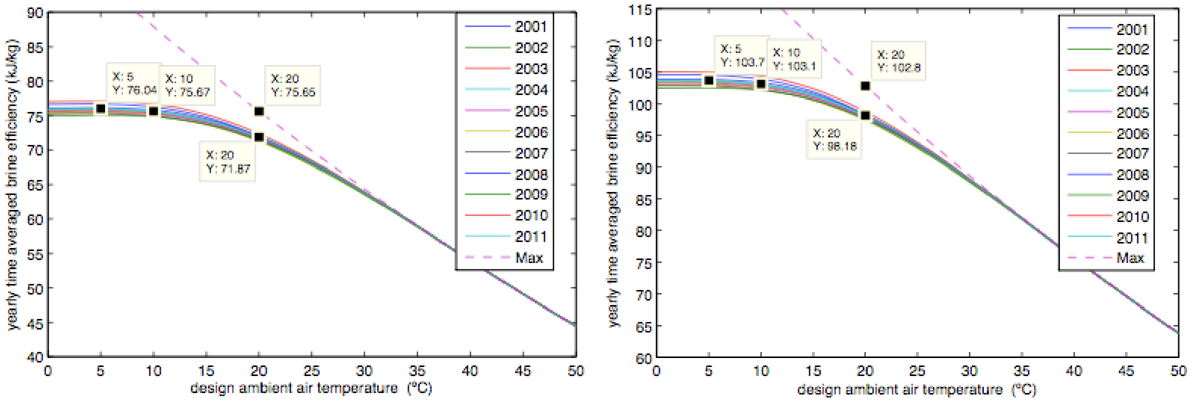


(a) Moomba data for $T_a^{\mathrm{GThF}} = 200°\mathrm{C}$ (b) Moomba data for $T_a^{\mathrm{GThF}} = 225°\mathrm{C}$

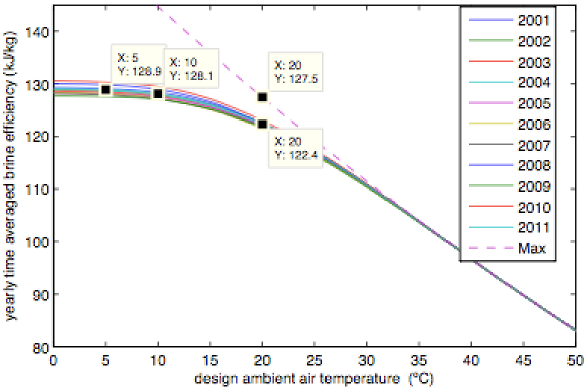


(c) Moomba data for $T_a^{\mathrm{GThF}} = 250°\mathrm{C}$

Figure 3: *Moomba site data for various geothermal fluid temperatures. The mean temperature at Moomba is 24°C. (Please note: The maximum brine efficiency line is the same line as shown in Figure (2), it is put here for ease of reference, but does not take into account any site data.)*

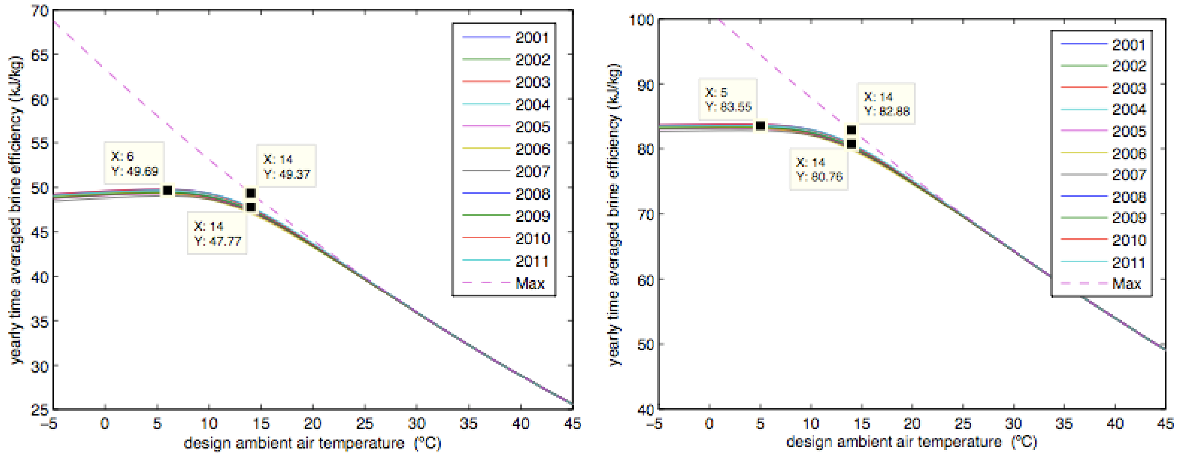


(a) Leigh Creek data for $T_a^{\mathrm{GThF}} = 175^\circ\mathrm{C}$ (b) Leigh Creek data for $T_a^{\mathrm{GThF}} = 200^\circ\mathrm{C}$



(c) Leigh Creek data for $T_a^{\mathrm{GThF}} = 225^\circ\mathrm{C}$

Figure 4: *Leigh Creek site data for various geothermal fluid temperatures. The mean temperature at Leigh Creek is 20°C. (Please note: The maximum brine efficiency line is the same line as shown in Figure (2), it is put here for ease of reference, but does not take into account any site data.)*



(a) Coonawarra data for $T_a^{\mathrm{GThF}} = 150^\circ\mathrm{C}$ (b) Coonawarra data for $T_a^{\mathrm{GThF}} = 175^\circ\mathrm{C}$

Figure 5: *Coonawarra site data for 150°C and 175°C geothermal fluid temperatures. The mean temperature in the Coonawarra is 14°C. (Please note: The maximum brine efficiency line is the same line as shown in Figure (2), it is put here for ease of reference, but does not take into account any site data.)*

Conclusion

Air-cooled binary Rankine cycle plants are significantly and adversely affected by varying ambient air temperature. However, while this loss is fundamentally due to the thermodynamics of the Rankine cycle, considering a site’s temperature distribution and the off-design effects of this distribution can allow for better choice in initial plant design.

By designing for a temperature which is colder than the mean site temperature a plant's output can be increased by 5-8%. Since, designing for a lower ambient temperature will increase initial plant costs (due to the requirement for a larger heat exchanger), in the final analysis, the capital costs will need to be weighed against ongoing improved production capabilities.

List of abbreviations

h	enthalpy (J/kg)
m	mass flowrate (kg/s)
p	pressure (kPa)
s	entropy (J/(kg/K))
c_p	heat capacity at constant pressure (J/(kg K))
P	power (W)
Q	heat flow per second (J/s)
T	temperature (°C)
ΔT	temperature difference (°C)
η_{brine}	brine efficiency (W-h/kg)
η_{th}	thermal efficiency (dimensionless)

Superscripts

CF	cooling fluid
GThF	geothermal fluid
cold	cold fluid
hot	hot fluid

Subscripts

1,2,3,4	State 1, 2, 3 or 4
a,b,c,d	State a, b, c or d
Amb	ambient state
in	heat added to the cycle
PP-C	pinch point in the condenser
PP-HX	pinch point in the heat exchanger

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