
OPTIMISATION OF GEOHERMAL SYSTEMS

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Signed Statement

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Abstract

In this thesis we investigate electricity generation using medium temperature geothermal fluids (150 - 225°C) harvested from amagmatic geothermal resources. This form of electricity generation has huge promise because: the size of the amagmatic resource is estimated to be ‘truly vast’, and geothermal energy is one of the few renewable energies capable of providing base-load electricity.

The definition of geothermal energy is ‘utilisable heat from the earth’. Where geothermal energy is easy to access, humans have been using it for millennia. Early humans used hot springs for bathing and cooking, and the world’s first geothermal district heating system was built in the 14th century (and is still in use today). Geothermal energy was first used to produce electricity in magmatic regions; we call this type of geothermal development a *conventional* geothermal development. The production of electricity from amagmatic geothermal developments (e.g. hot rocks, hot sedimentary aquifers) began in the 1970s and is still predominantly in a research and development phase; we call this type of geothermal development an *unconventional* geothermal development.

In order to determine the best performance measures for financial decision making regarding geothermal developments, we compare and contrast current performance measures in the geothermal industry. We show that enthalpy efficiency, categorised by reservoir enthalpy, is the best financial performance measure because it is the same as other measures on most criteria, and superior in terms of comparability across different geothermal sites.

Geothermal Assisted Power Generation (GAPG) is a very promising method of generating electricity from an unconventional geothermal resource. GAPG uses a hot geothermal fluid to generate extra electricity from a traditional fossil-fuel fired steam power plant. This means that GAPG requires a geothermal resource to be located close to a fossil-fuel fired steam power plant. Pairing an unconventional geothermal resource with an existing power plant is the most likely way to make this happen. GAPG is attractive because it generates more electricity per kilogram of geothermal fluid than traditional binary Rankine cycle technology; and, perhaps more importantly, it allows unconventional geothermal developers to concentrate solely on producing a hot geothermal fluid, and not on electricity generation.

Some of the most attractive unconventional geothermal resources exist a long way from sources of cooling water. Hence, it is important to understand the effect of using air to cool the working fluid in power generation facilities. In particular, we investigate the effect of using air to cool binary Rankine cycle power plants. Initially, we construct a mathematical model, which models the effect of varying ambient-air-temperature on the power output of air-cooled binary Rankine cycle plants. Using this model we show that, when the observed ambient-air-temperature is greater than the design ambient-air-temperature, plants lose 10-20% productivity for every 10°C increase in the observed ambient-air-temperature. In contrast, there is no productivity gain when the observed ambient-air-temperature is less than the design ambient-air-temperature.

Using this result, it is intuitive, but inaccurate, to assume that the optimal design ambient-air-temperature at a given site should be the coolest observed ambient-air-temperature at that site. Hence, we subsequently use this model to investigate the optimal design ambient-air-temperature at 12 different sites in Australia using 13 years of historical temperature data. We conducted this optimisation in two ways: 1. based on total energy output from an air-cooled organic Rankine cycle plant (which we called the ‘production optimisation model’); and 2. based on expected revenue from an air-cooled organic Rankine cycle plant (which we called the ‘revenue optimisation model’).

Due to higher ambient-air-temperatures, electricity prices are generally higher in summer, in South Australia. Conversely, due to higher ambient-air-temperatures, production levels in an air-cooled binary Rankine cycle plant are generally lower in summer. Hence, we expected that the production optimisation model would yield different results to the revenue optimisation model.

Using the production optimisation model, our results show that the total energy output from air-cooled organic Rankine cycle plants could be increased by around 5% if the design ambient-air-temperature was reduced below its traditional value of the mean ambient-air-temperature to the optimal design ambient-air-temperature. Using the revenue optimisation model, our results show that the expected plant revenue of an organic Rankine cycle plant could be increased by around 4.5% by decreasing the design ambient-air-temperature below its traditional value to the optimal design ambient-air-temperature. The optimal design ambient-air-temperatures determined using the production optimisation model are generally 1-2°C lower than those determined using the revenue optimisation model.

This style of general insight research is particularly useful early in the development cycle of a new technology because it enables investment to be targeted more appropriately. This means that future investments, whenever they occur, can now be targeted more precisely and gives greater hope that geothermal energy may play a significant role in the future energy system.

Further, this research is not limited to medium temperature, unconventional resources. It could equally be applied to any medium temperature fluid: For example,

low grade conventional geothermal resources, co-produced water from oil and gas wells, or waste water from high grade conventional geothermal resources.

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Nomenclature

Notes on nomenclature

We have attempted to make the definitions of each variable clear throughout the thesis. However, to aid the reader, we define commonly used variables here. Further, we have added chapter specific nomenclatures at the end of Chapters 3 - 8.

Throughout this thesis, the following conventions are followed:

1. Unless otherwise stated, all units are SI units.
2. Where a thermodynamic variable can have an extensive or intensive form, a capital letter is used to represent the extensive variable and a small letter is used to represent the intensive variable. For example: H is enthalpy as an extensive variable, which is measured in joules J ; while h is specific enthalpy, which is measured in $J\text{ kg}^{-1}$.
3. A dot over the top of a thermodynamic variable indicates it is a rate variable. For example: \dot{h} is the rate of specific enthalpy, which is measured in $J\text{ (kg s)}^{-1}$.
4. Superscripts are used to indicate which fluid a thermodynamic variable refers to. For example: h^{GTh} indicates the specific enthalpy of the geothermal fluid.
5. Subscripts are used to indicate the place, state, flow or piece of equipment that the variable refers to. For example: h_a^{GTh} indicates the specific enthalpy of the geothermal fluid at State a, $\eta_{\text{condenser}}$ is the efficiency of the condenser.

We have attempted to avoid using the same notation to represent more than one variable. However, due to the wide range of topics covered in this thesis, and our desire to follow well recognised conventions, this has not always been possible. In particular, we note:

1. In Chapter 1 through to Chapter 6, t indicates time. However in Chapter 7 and Chapter 8, t is used to represent the individual occurrence of the temperature random variable T .
2. In Chapter 1 through to Chapter 6, E indicates energy. However in Chapter 7 and Chapter 8, the operator $E[.]$ is used to represent the expectation of a random variable.
3. η is used to represent *efficiency* which is dimensionless, except for the specific case of η_{brine} , which represents *brine effectiveness* which has units of kW kg^{-1} .

Nomenclature

C_p, c_p	heat capacity at constant pressure (J (K)^{-1}) and specific heat capacity at constant pressure (J (kg K)^{-1})
H, h	enthalpy (J) and specific enthalpy (J kg^{-1})
m	mass (kg)
P	power ($\text{W} = \text{J s}^{-1}$)
p	pressure (Pa)
Q, q	heat (J) and specific heat (J kg^{-1})
S, s	entropy (J (K)^{-1}) and specific entropy (J (kg K)^{-1})
T	temperature ($^{\circ}\text{K}$)
W, w	work (J) and specific work (J kg^{-1})
HV	heating value (J kg^{-1})
Δ	difference (e.g. ΔT is temperature difference).
η	efficiency (dimensionless)
ψ	specific exergy (J kg^{-1})

Superscripts

GTh	geothermal fluid
WF	working fluid (in fossil-fuel fired steam power plants the working fluid is called the feedwater)

Functions

$_{x,y}f_z^{\alpha}(\cdot, \cdot)$	the function which calculates state variable z of fluid α , using state variables x and y , assuming that fluid α is in the liquid, vapour, gas, or supercritical region.
${}_x\dot{f}_z^{\alpha}(\cdot, \cdot)$	the function which calculates the state variable z of fluid α using variable x , assuming that fluid α is a saturated vapour.
${}_x\dot{f}_z^{\alpha}(\cdot, \cdot)$	the function which calculates the state variable z of fluid α using variable x , assuming that fluid α is a saturated liquid.
$_{x,y}\hat{f}_z^{\alpha}(\cdot, \cdot)$	the function which calculates state variable z of fluid α , using state variables x and y , assuming that fluid α is in the 2-phase region.