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Thermodynamic and economic analysis for the pre-feasibility study of a binary geothermal power plant

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ABSTRACT

Maximum power output and thermal conversion efficiency are the goals of ORC thermodynamic analysis. Co-optimization of energetic performance and system cost is needed for pre-feasibility design analysis. This paper presents a pre-feasibility design investigation for a binary geothermal power plant using a typical geothermal resource in New Zealand. Thermodynamic and economic analyses were conducted for key cycle design options, a range of working fluids and component selection parameters. The net electrical power output (Wnet) and the ratio of Wnet to total Purchased Equipment Cost (PEC) are used as the objective function to select the most thermo-economical designs. Three working fluids n-pentane, R245fa and R134a are investigated. The thermodynamic analysis shows that the net electrical power output (Wnet) of cycle design achieves a maximum level at a certain optimum turbine inlet pressure and mass flow rate of working fluid. The 2-stage designs produce higher Wnet and thermal and exergy efficiencies than the 1-stage designs. Economic comparison indicates that the type of working fluid and cycle configuration have a great effect on economic performance as measured by PEC. The profitability analysis was conducted for the top three options. The results indicate that a standard Rankine cycle with a 2-stage turbine using n-pentane is the most thermo-economical design for the particular brine resource and re-injection conditions.

1. Introduction

Renewable electricity generation will continue to be supported by the energy policy of most countries. Intermittency of wind and solar PV reduce the utilization factor and limit the total capacity that can be installed in a grid. Base load renewables, hydro and geothermal, are by far the largest renewable electricity contributors internationally. Geothermal energy is considered renewable heat energy which comes from beneath the earth surface with temperatures varying from 50 to 350 °C [1]. A geothermal reservoir is in fact a finite resource, but if the reservoir is operated well below the potential peak production rate, and if the brine is re-injected into the geological thermal zone, then many power plants can be designed to run through their plant lifetime. Geothermal power generation has a large worldwide potential for further development [2].

Three major types of the geothermal power plant are dry-steam plants, flash-steam plants and binary-cycle plants [3]. Most power plants utilize a combination of steam, bottoming and binary power generation, depending on the resource production characteristics. High pressure, high temperature brine is most efficiently used by flash separation and expansion of the steam through a steam turbine. Organic Rankine cycle (ORC) binary power plants are utilized for medium and low temperature sources, and as a bottoming cycle for the steam turbine. Unlike coal or gas-fired power plants, the ORC binary units must be designed specifically to best utilize the temperature and flow available from the particular geothermal resource. An additional design consideration is the reinjection temperature limit required to avoid excessive mineral scale deposition in the ORC evaporator heat exchanger. This work focuses on ORC binary geothermal power plants, and presents a thermo-economic approach to cycle and component design and co-optimization for performance and cost.

Selection of the ORC working fluid is of primary importance for all cycle and component analysis. The relationship between working fluid structure and thermodynamic properties and the cycle thermodynamic performance has been analyzed by several authors. Saleh et al. [4], Quoilin et al. [5] and Shengjun et al. [6] analyzed different working fluids for low temperature applications, and concluded that hydro-fluorocarbons with low critical temperature such as R245fa and R134a are suitable for binary ORC's. Aghahosseini et al. [7] investigated different pure and zeotropic-mixture working fluids for power generating application

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Nomenclature

1-Stage_Rec	one stage, recuperative cycle
1-Stage_Std	one stage, standard cycle
2-Stage_Rec	two stage, recuperative cycle
2-Stage_Regen	two stage, regenerative cycle
2-Stage_Std	two stages with standard cycle
C	cost ($)
DPB	Discounted Payback (year)
EDR	exchanger design & rating
G	generator
h	specific enthalpy (kJ/kg)
I	cost index
$\dot{m}$	mass flow rate (kg/s)
N	lifetime of the plant (year)
NPV	Net Present Value ($)
ORC	Organic Rankine cycle
PEC	purchase equipment cost ($)
Pr	pressure ratio
Q	heat transfer rate (kW)
q	discount rate (%)
R	annual revenues ($)
s	specific entropy (kJ/kg $*$ K)
SIC	specific investment Cost ($)
t	time (year)
Tank	feed water heater tank
TCI	total capital investment ($)
V	tank volume (m^3)
Wnet	net electrical power output (kW)
W_t	net power of turbine (kW)
W_p	net power of pump (kW)
W	work inputs (kW)
X	fraction of flow rate
Y	power of pump or a turbine (kW

Greek symbols

η_e	exergy efficiency (%)
η_{th}	thermal efficiency (%)
γ	investment ratio

Subscripts

Brine	geothermal fluid
Eva	evaporator
In	input
New	time when the cost is desired
Old	base time
Out	output
p	pump
T	turbine

at different operating conditions using a parametric sensitivity. The thermodynamic cycle performance indicators used were energy and exergy efficiencies, cycle reversibility rate, external heat requirement and mass flow rate. They mentioned that the working fluid significantly affects the cycle performance.

Fig. 1 gives the basic ORC plant schematic diagram and TS diagram for 1-stage turbines, and Fig. 2 gives the different cycle configurations for 2-stage ORC's. Thermodynamic cycle design, or cycle configuration, also directly impacts ORC system performance [8]. However, only few publications discuss the thermodynamic cycle design. Mago et al. [9] evaluated and compared the basic and regenerative ORC configurations utilizing dry organic working fluids. They concluded the regenerative ORC has higher first and second law thermodynamic efficiencies as well as lower irreversibility.

Investigation of ORC plant cost and design has likewise appeared in relatively few reported research investigations. Hettiarachchi et al. [1] analyzed the ORC performance for ammonia, n-pentane, HCFC-123 and PF 5050. They used a ratio of total heat exchanger to net power output as the objective function. They found that power plant cost is sensitive to the choice of working fluid. Meinel et al. [10] evaluated the implementation of a two stage ORC with regenerative pre-heating and they compared between the standard and recuperative ORC cycles. They concluded that the two stages ORC with regenerative pre-heating has the highest thermodynamic and economic performance. Yari et al. [3] and Coskun et al. [11] performed a comparative study of different geothermal power plant concepts based on the first and second laws of thermodynamics to investigate the optimum electricity production from certain geothermal resources. Yari et al. [3] showed that a regenerative organic Rankine cycle with internal heat exchanger is a good option to be further studied in detail. Coskun et al. [11] investigated both thermodynamic and economic aspects of most current types of ORC configuration: single-flash, double flash, flash-binary, simple ORC, ORC with an internal heat exchanger, regenerative ORC, regenerative ORC with an internal heat exchanger and Kalina cycle plants. They summarized that Kalina cycle presents a viable choice of both thermodynamic and economic aspects.

Most of the investigations reported in the literature do not consider realistic absolute pressure levels as a constraint when calculating the turbine performance during the thermodynamic analysis. According to Moustapha et al. [12], the pressure ratio, actual inlet and exit pressures expected must be matched to accurate models of the turbine. When the turbine runs at off-design absolute pressure, there will be a difference in Reynold numbers that might impact on its performance to varying degrees, depending on the type and design of the turbine.

The main objective of the present study is to perform comparative thermodynamic and economic analysis of different binary geothermal power plant configurations as required for pre-feasibility design. The configurations consist of one and two-stage designs with cycle enhancements of either recuperator or regenerator. In order to improve the accuracy of the turbine models, a constant pressure ratio and an absolute pressure level consistent with known turbines was used for every working fluid. A case study was implemented for the feasibility design study using actual geothermal well and cooling water data from a location in the Taupo Geothermal Zone (TGZ) in New Zealand, as shown in Table 1. The geothermal outlet temperature is constrained to be >45 °C to avoid silica precipitation in the reinjection wells (note that the temperature is valid for the specific site and may be different for other geographic boundary conditions).

2. Methodology

The working fluids considered in this feasibility study are R245fa, n-pentane and R134a as these are most commonly used in the commercial ORC units. The thermodynamics cycle design parameters are based on standard assumptions for superheat, subcooling, pinch point for heat exchangers and nominal performance for components as shown in Table 2. These values are commonly used by ORC researchers. The pressure ratio of 3.5 is based on the literature study conducted by Bao et al. [13]. They summarized that the range of this value for Radial-inflow turbine is between 1.1 and 6.3. Furthermore, the pressure ratio of the Chena hot spring 400 kW geothermal power plant [14] is fairly close at 3.65. The