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Comparison of sub- and supercritical Organic Rankine Cycles for power generation from low-temperature/low-enthalpy geothermal wells, considering specific net power output and efficiency

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HIGHLIGHTS

► Geothermal power generation from low-temperature sources of around 150 °C.
► Simulation of sub- and supercritical Organic Rankine Cycles.
► Propane, CO_2 and 10 other refrigerants as working fluids investigated.
► Power output optimization by variation of the steam conditions.
► Increase of power output with supercritical cycles and suitable working fluid.

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ABSTRACT

Electrical power production at low-enthalpy (~150 °C) geothermal sites is usually realized using an Organic Rankine Cycle (ORC process). This paper presents our analysis of sub- and supercritical processes using propane, carbon dioxide and ten other refrigerants as working fluids. The impact of crucial indicators for optimization, such as specific net power, thermal efficiency and heat input is discussed in detail.

The focus was to optimize the thermodynamic loop and the influence of other parameters, such as condensing temperature, minimal temperature difference in the heat exchanger, and internal heat recovery. Simulations showed that at a geothermal fluid temperature of 150 °C, a suitable working fluid such as propane or R143a can increase specific net power output up to 40%.

Furthermore, systematic simulations on brine temperatures of 130–170 °C from subcritical to supercritical operation are discussed.

Results from this research may also be applicable for electricity generation using waste heat from combined heat and power (CHP) plants or other technical processes.

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1. Introduction

In a sustainability context, intelligent provision of energy is a key challenge for the 21st century. Using renewable energy sources to hedge against rising costs of fossil fuels and reduce greenhouse gas emissions is essential. In addition to hydropower, wind and solar energy, geothermal energy offers great potential for power generation, particularly for base load power without need of storage. As of 2010, geothermal power plants with a capacity of ~10 GW_{el} were in operation worldwide, principally at high enthalpy reservoirs like the pacific ring of fire [1].

Typically, use of geothermal fluid in a power plant cycle assumes high fluid temperatures. In order to use geothermal energy in "non-hot spot" areas, or *low-enthalpy reservoirs*, power generation is realized using binary cycles [2]. In this case geothermal fluid with temperatures of 100–200 °C is pumped from rock layers deep within the earth, where its heat is then transferred in a heat exchanger to a working fluid. Thermal energy is then converted to electricity via a low-temperature cycle. This thermodynamic cycle with an organic working fluid is referred to as Organic Rankine Cycle (ORC).

The choice of working fluid significantly influences the maximum achievable performance. Saleh et al. [3] investigated 31 different working fluids with geothermal fluid temperatures of 100–130 °C. They concluded that the greatest efficiency can be achieved using subcritical cycles and an internal heat exchanger.

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Nomenclature

c_p	specific isobaric heat capacity
h	specific enthalpy
$\dot{m}$	mass flow
p	pressure
P	power
$\dot{Q}$	heat flow
q	specific heat
T	temperature
s	specific entropy
w	specific work
η	efficiency

Subscripts

C	Carnot
crit	critical point/parameter
geo	geothermal fluid
in	in
max	maximum
min	minimum
ORC	Organic Rankine Cycle
out	out
pump	pump
s	isentropic
spec	specific
th	thermal
triangle	triangle
turbine	turbine

Lakew and Bolland [4] simulated subcritical ORCs at geothermal fluid temperatures of <200 °C with six different working fluids; R227ea at 80–160 °C geothermal fluid temperature and R245fa at 160–200 °C yielded the highest efficiencies. Heberle and Brüggemann [5] calculated subcritical ORC's for geothermal fluid temperatures of <177 °C with a special interest on combined heat and power production. Schuster et al. [6] analyzed supercritical cycles with various working fluids and different heat sources and concluded a possible improvement of the net power output.

In this study, the potential of sub- and supercritical low-temperature processes using propane, CO_2 and ten other refrigerants as candidate working fluids was investigated. Power plant processes were modeled and simulated using an in-house program, GeSi (Geothermal Simulation). The program optimizes the thermodynamic process according to vapor parameters. Substance thermodynamic data were taken from REFPROP 8.0 of the National Institute of Standards and Technology [7]. The GeSi program was validated using IpsePro (Version 4.0, SimTech Simulation Technology) for isopentane as a reference fluid. The aim of this investigation was performance optimization based on live vapor parameters; the processes are simulated over a wide range of live vapor pressures and temperatures. Dependencies between reinjection temperature of the geothermal fluid, supplied heat, thermal efficiency and the net power of the process are discussed in detail.

Results obtained here are also compared with isopentane (reference fluid), a common working fluid in existing geothermal power plants.

Important cycle parameters, such as condensing temperature, minimal temperature difference (MTD) or *pinch point*, and use of an internal heat exchanger, were varied to investigate their influence on the overall net power output. Cycles employing other working fluids at geothermal fluid temperatures of 130–170 °C have been investigated to show a generalized relation between the critical temperature of suitable working fluids, the geothermal fluid temperature and the maximum achievable net power output.

2. Modeling

2.1. Organic Rankine Cycle

The Rankine cycle, using water as a working fluid, is state-of-the-art in coal, gas and nuclear power plants. Water, however, is not a suitable working fluid for converting low-temperature heat, due to high evaporation temperature at ambient pressure; therefore, in Organic Rankine Cycles (ORCs) organic fluids with lower vaporization temperatures are used.

Fig. 1 shows the ORC using propane as a working fluid in the T–s-diagram, as well as process flow. The working fluid is compressed in the feed pump, heated up and evaporated in the heat exchanger before it is expanded in the turbine. In the last step, which closes the cycle, the remaining heat is removed in the condenser. Changes in state of an ideal process are as follows:

- 1–2: isentropic compression, supply of work to the cycle
- 2–3: isobaric supply of heat (heat exchanger)
- 3–4: isentropic expansion, submission of work out of the cycle
- 4–1: isobaric removal of heat (condenser).

Depending on the pressure at which the heat is supplied, the process is either subcritical, with the fluid evaporating as it passes through the two-phase region (bold line, Fig. 1), or supercritical (dotted line, Fig. 1). Location of the critical point (CP) depends on the fluid.

From the enthalpy differences between the individual state points, the specific energy contribution of each component can be calculated:

- Work supplied in the feed pump: $w_{\text{pump}} = h_2 - h_1$
- Heat supplied in the heat exchanger: $q_{\text{in}} = h_3 - h_2$
- Specific work of the turbine: $w_{\text{turbine}} = h_3 - h_4$
- Heat removed in the condenser: $q_{\text{out}} = h_4 - h_1$

By this the thermal efficiency of the cycle can be calculated

$$\eta_{\text{th}} = \frac{|q_{\text{in}}| - |q_{\text{out}}|}{|q_{\text{in}}|} = \frac{|w_{\text{turbine}}| - |w_{\text{pump}}|}{|q_{\text{in}}|} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} \tag{1}$$

The previously described process is an ideal case, that in reality is affected by losses. Pressure losses in the pipes, heat exchanger and condenser cannot be avoided. In addition, there are losses during compression in the pump and expansion in the turbine. These losses result in an increase in entropy during compression and expansion.

This can be described with the isentropic pump and turbine efficiency

$$\eta_{\text{pump}} = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{2}$$

$$\eta_{\text{turbine}} = \frac{h_3 - h_4}{h_3 - h_{4s}} \tag{3}$$

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