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Working fluid parametric analysis for regenerative supercritical organic Rankine cycles for medium geothermal reservoir temperatures

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Abstract

The conversion efficiency of geothermal energy is very low. For low-temperature resources, such as geothermal energy, a supercritical organic Rankine cycle (ORC) has been shown to be more efficient than an ORC. Regenerative supercritical ORCs have been proven to yield even higher efficiencies for cases where the heat source is limited above the ambient temperature. Most studies on these cycles have focused on turbine inlet temperatures between 80 and 130˚C. Only a few studies have explored other working fluids between 180 and 350˚C but did not analyze optimum turbine inlet pressures. Turbine inlet temperatures ranging from 170 to 240˚C were tested with the heat source provided by a medium temperature geothermal reservoir. A parametric analysis was performed for various turbine inlet pressures and temperatures. The fluids tested included cis-butene, pentane, isopentane, butane, isobutane, carbon dioxide, neopentane, propylene, and propane. Temperatures and pressures were selected for each tested fluid to achieve maximum first law efficiency, second law efficiency, cycle effectiveness, and net work.

Keywords: environmental working fluids; geothermal; supercritical organic Rankine cycle; geothermal efficiency; renewable energy; recuperator

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1. Introduction

Heat engines using low-temperature resources, such as geothermal reservoirs, are limited by their low conversion efficiency. Currently, geothermal energy provides 10 gigawatts of electric power and has the potential and the resource to grow exponentially [1]. For geothermal energy to be utilized to its fullest capacity, its conversion efficiency needs to be improved. For high temperature reservoirs above 220˚C, the geothermal brine is flashed into steam to be used directly for power generation. For dry steam, single flash, and double flash plants, the efficiency ranges from around 6 to 15% on average for heat reservoirs with an enthalpy between 900 to 2,900 kJ/kg [2]. The downfalls of flash steam plants are the noncondensable gases and salt content that add corrosion to the system and reduce turbine efficiency [2]. A binary system is the most common type of geothermal power plant for medium to low temperature reservoirs (up to 200˚C) where the liquid is dominant [3]. In a binary system, the geothermal brine exchanges heat with an organic fluid which is used to run a cycle, such as an organic Rankine cycle (ORC)[3]. Many studies have explored the optimization of ORCs. However, supercritical ORCs can achieve higher efficiencies than subcritical ORCs at low-temperature [4–8]. Supercritical ORCs are also advantageous over subcritical cycles as they have a better thermal match (thermal glide) between the working fluid and the heat source such as geothermal energy. Li et al. found supercritical ORC performed better for once through heat sources such as geothermal reservoirs [9].

A regenerative cycle can further improve the efficiency of the system over a simple cycle. A few analyses have compared a regenerative supercritical ORC to a simple supercritical ORC. Glover et al. analyzed fluid performance with a turbine inlet temperature between 100 and 350˚C with a maximum cycle pressure of 5 bar greater than the critical point. The best performance was found when the critical temperature of the fluid was just below the temperature of the heat source. Fluids with high critical temperatures were also more tolerant of temperature and pressure changes in the condenser [10]. Le et al. used a genetic algorithm to maximize the first law and system efficiency for various fluids at a turbine inlet temperature of 139˚C. Carbon dioxide performed the worst at the analyzed conditions. A recuperative cycle was also found to achieve higher efficiencies than a simple cycle [11].

Toffolo et al. studied various supercritical configurations of supercritical ORCs including a regenerative cycle for isobutane and R134a with turbine inlet temperatures between 130 and 180˚C. It was found that for the tested range, isobutane performed better in a subcritical cycle while R134a performed better in a supercritical cycle [12]. Astolfi et al. analyzed supercritical and subcritical ORCs for medium-low temperature geothermal sources (120 to 180˚C) to optimize system performance in relation to cost [13].

Supercritical ORC studies have focused on turbine inlet temperatures of 80˚C to 130˚C. Supercritical ORCs with carbon dioxide cycles have been analyzed up to 800˚C. Performance in respect to various pressures has not been explored for regenerative supercritical ORCs for turbine inlet temperatures between 170 to 240˚C. This paper studies environmental fluids with critical temperatures below 200˚C in a regenerative supercritical ORCs to improve the conversion efficiency of geothermal energy.

Nomenclature

General		Subscripts			
h	specific enthalpy (kJ/kg)	I	first law	t	turbine
$\dot{m}$	mass flow (kg/s)	II	second law	p	pump
$\dot{Q}$	rate of heat (kW)	a	ambient	WF	working fluid
T	temperature (K)	L	low		
$\dot{W}$	power (kW)	H	high		
		hr	heat rejection		
Greek Letters		hs	heat source		
ε	effectiveness	m	mechanical		
η	efficiency	s	isentropic		