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Thermodynamic analysis of a simple Organic Rankine Cycle

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ABSTRACT

Thermodynamic performance (thermal efficiency and net power output) of a simple subcritical and supercritical Organic Rankine Cycle (ORC) was analyzed over a range of operating conditions for a number of working fluids to determine the effect of operating parameters on cycle performance and select the best working fluid. The results show that for an ORC operating with a dry working fluid, thermal efficiency decreases with an increase in the turbine inlet temperature (TIT) due to the convergence of the isobaric lines with temperature. The results also show that efficiency of an ORC operating with isentropic working fluids is higher compared to the dry and wet fluids, and working fluids with higher specific heat capacity provide higher cycle net power output.

New expressions for thermal efficiency of a subcritical and supercritical simple ORC are proposed. For a subcritical ORC without the superheat, thermal efficiency is expressed as a function of the Figure of Merit (FOM), while for the superheated subcritical ORC thermal efficiency is given in terms of the modified Jacob number. For the supercritical ORC, thermal efficiency is expressed as a function of dimensionless temperature.

1. Introduction

Organic Rankine Cycle (ORC) has a potential to play a significant role in energy conversion, especially in the low-temperature and Combined Heat and Power (CHP) applications. In the U.S., approximately 60% of heat derived from the primary energy sources is rejected to the environment as a waste heat [1]. An ORC offers power generation from the renewable, waste heat and low- and medium-grade heat sources such as: geothermal, solar, biomass, and waste heat from the industry, primary movers, and thermal power plants. Refrigerants and hydrocarbons are considered as suitable working fluids for the ORC.

This study is focused on a simple ORC using solar and geothermal heat sources and different working fluids. Many papers and studies are dedicated to a solar-powered ORC and working fluid selection [2–6]. Also, many researchers are working on the ORC using geothermal heat source [7–11]. Chen et al. [12] considered pure working fluids for the subcritical and supercritical ORC. Shengjun et al. [13] performed parametric optimization and comparison of different working fluids for the subcritical and transcritical ORC using geothermal heat source. He also studied selection criteria for evaluation of different working fluids. Saleh et al. [11] evaluated 31 different working fluids suitable for a geothermal ORC, studied different work cycle configurations, and compared different working fluids in terms of thermal efficiency. Lakew and Bolland [14] analyzed the effect different working fluids on thermal efficiency of a simple subcritical ORC operating in the 80–160 °C temperature range.

Numerous criteria are considered during the fluid selection procedure. Also, international protocols and agreements stipulate the use working fluids that are not harmful to the environment. Thus, the criteria such as ozone depletion potential, flammability, toxicity and global warming potential (GWP) need to be considered during the working fluid selection process. Papadopoulos et al. [15] used 15 criteria for the fluid selection; with environmental, safety, physical, chemical and economical properties being the five main groups. The best working fluid is selected based on the cycle thermal efficiency. Details are provided in Ref. [16].

There is no working fluid that satisfies all selection criteria [17], thus the fluid selection method balancing the environmental, safety, physical, and chemical properties of a working fluid, capital investment (system cost), manufacturing, maintenance requirements, and cost should be used. The selection processes may

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Nomenclature

C_P	Specific heat [kJ/kg.k]
h	Enthalpy [kJ/kg]
h_{fg}	Latent heat [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
P	Pressure [MPa]
q	Heat rate [kJ/kg]
s	Entropy [kJ/kg.k]
T	Temperature [k]
$\dot{W}$	Work [kw]

Greek symbols

η	Efficiency

Subscript

1–5	State points in the cycle
c	Compressor
cr	Critical point
eq	Equivalent
ev	Evaporation
f	Working fluid
in	Inlet
max	Maximum
min	Minimum
net	Net
out	Outlet
r	Dimensionless
t	Turbine
th	Thermal

Acronyms

CHP	Combined heat and power
EPV-11	Ebsilon Professional V11
FOM	Figure of merit
GWP	Global warming potential
Ja	Jacob number
ODP	Ozone depletion potential
ORC	Organic Rankine cycle
SP	State point
TIT	Turbine inlet temperature

be divided into two groups: elimination and ranking [18]. In the first step, elimination is used to reject unsuitable working fluids before the ranking process is applied. Roedder et al. [19] considered 22 criteria divided into six main groups, and then used a combination of the elimination and ranking methods for selection of the working fluid. Different weights were considered for each property of a working fluid. The approach was applied to a two-stage ORC, and Isobutane was identified as the best working fluid.

A number of scholars has recently conducted research concerning performance optimization of the ORC. Roy et al. [20] presented a parametric optimization process for a regenerative ORC, while He et al. [21] presented a theoretical analysis for determining the optimum evaporation temperature. Wang et al. [22] developed a theoretical model for thermal efficiency in terms of the Jacob number. Also, Kuo et al. [23] proposed a Figure of Merit (FOM) and showed that efficiency of a subcritical ORC decreases with an increase in FOM. However, the relationship between thermal efficiency and FOM was not presented, and Kuo's definition of FOM is applicable to the subcritical ORC cycle only.

A simple ORC was considered in this study where the effect of different working fluids on the cycle power output and thermal efficiency was investigated over the range of operating conditions to identify the best working fluid. Three expressions for the cycle thermal efficiency η_{th} were developed for the subcritical, superheated subcritical, and supercritical simple ORC. The cycle calculations and simulations were performed by employing the Ebsilon Professional V11 (EPV-11) power systems modeling software [24]. EPV-11 is a professional software for detailed design, analysis, and optimization of power generation systems.

2. Thermodynamic modeling and working fluid properties

The operating principles of the ORC and Rankine cycle are the same: compression of the liquid, phase change (evaporation) in the evaporator, expansion in the turbine (expander), and phase change (condensation) in the condenser. The main components of the simple ORC (feed pump, evaporator, turbine, and condenser) are presented in Fig. 1. The feed pump delivers working fluid to the evaporator where the working fluid is evaporated at approximately

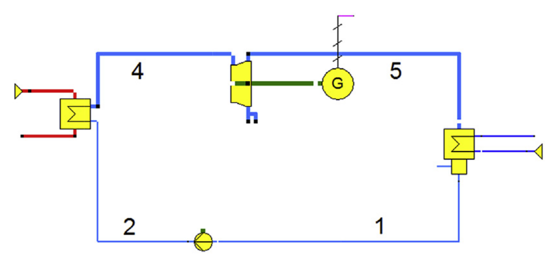

Fig. 1. Schematic of the simple ORC.

constant pressure using the externally supplied heat. A superheater is used in some ORC designs to superheat the working fluid. The saturated or superheated working fluid is expanded in the turbine (expander), which is driving an electric generator. The low-pressure, low-temperature working fluid leaving the turbine is condensed in the condenser. The pressure of the working fluid leaving the condenser as a saturated (or slightly subcooled liquid) is increased by the feed pump, completing the power cycle. Depending on type of the working fluid, a recuperator may be placed ahead of the condenser to recover heat and transfer it to the working fluid leaving the feed pump. This configuration is referred to as the recuperated ORC.

The T-s diagrams of the simple subcritical and supercritical ORCs are presented in Fig. 2. For the subcritical cycle, the working fluid undergoes phase change in the evaporator, and in case of the superheated subcritical cycle it is superheated in the superheater prior to entering the turbine. There is no phase change in the supercritical cycle where the working fluid remains as a homogeneous supercritical fluid throughout the entire power cycle.

2.1. Thermodynamic and environmental properties of working fluids

The choice of the working fluid for the ORC has a significant effect on the cycle performance. 23 different working fluids were evaluated in this study to determine the best working fluid and