Energy 86 (2015) 93–104

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Organic Rankine cycle model for well-described and not-so-well-described working fluids

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A R T I C L E I N F O

Article history:
Received 23 October 2014
Received in revised form
3 March 2015
Accepted 25 March 2015
Available online 21 May 2015

Keywords:
Equation of state
Organic Rankine cycle
Peng-Robinson
Simulation model
Working fluids

A B S T R A C T

This paper presents an ORC (organic Rankine cycle) model consisting of turbine, condenser, pump, and boiler, with an optional IHX (internal heat exchanger). The model includes well-described (considerable experimental data) working fluids using the high accuracy EoS (equations of state) contained in REFPROP. Moreover, and more importantly, the model allows one to quickly and easily create from a few to many thousands of P-R (Peng-Robinson) EoS for not-so-well-described (little or no experimental data) working fluids. The latter is realized by parametrically varying critical temperature (T_c), critical pressure (P_c), acentric factor (ω), and ideal gas specific heat ($c^o_{p,c}$). Simulation results for a low-temperature ORC application show that efficiency (η) increases with increasing heat source temperature (T_{max}), and does so more strongly when an IHX is included; whereas, volumetric work output (V) decreases with increasing T_{max}. The results further show that both η and V strongly decrease with increasing heat sink temperature (T_{cond}). Parametrically varying T_c, P_c, ω, and $c^o_{p,c}$ showed that: (1) Increasing T_c generally leads to higher η and lower V. (2) Increasing P_c monotonically increases V. (3) Variations in ω do not significantly impact η or V. (4) η and V both generally decrease with increasing values of $c^o_{p,c}$.

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1. Introduction

There is growing interest in ORC (organic Rankine cycles) for the production of electrical energy from renewable energy sources (e.g., solar, geothermal, biomass) or from "waste heat" from industrial processes, fuel cells, and the like. For our purposes, what distinguishes renewable energy/waste heat sources from conventional energy sources (e.g., hydrocarbon fuels) are the much lower source temperatures for the non-conventional energy sources. This fact implies the high-side temperatures (saturation temperatures of the working fluid in the boiler for subcritical cycles) will be lower for Rankine cycles based on non-conventional energy sources than for ones based on conventional energy sources making working fluids derived from organic compounds more appropriate ("ideal") than water for cycles based on non-conventional energy sources. This is the reason such cycles are often dubbed organic Rankine cycles.

In recent years, research and development and the resulting literature regarding ORC machines, applications, energy sources, and working fluids has been rapidly increasing. Here, only a few recent papers regarding primarily low-temperature energy sources will be discussed.

Peris et al. [1] bench tested an ORC machine designed for low grade heat sources and showed that the cycle thermal efficiency increased as a function of increasing source temperature. Carcasci et al. [2] simulated an ORC for the recovery of waste heat from gas turbine engines. They considered four commonly existing working fluids and determined the choice of the "best" working fluid depended on the source temperature. Prando et al. [3] experimentally and numerically studied an ORC biomass application for district heating CHP (combined heat and power) in Northeast Italy and showed this to be a technically and economically viable approach for increasing the use of renewable energy resources in the production of electric energy in these types of applications. Tchanche et al. [4] discussed six different ORC architectures (basic, superheated, transcritical/supercritical, with IHX (internal heat exchanger), with reheating, and with integrated feedliquid heaters), five different heat resources (biomass, ocean, waste heat, geothermal, and solar), the types of applications for ORC machines, and characteristics of ORC machines, including listing some

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http://dx.doi.org/10.1016/j.energy.2015.03.119
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Nomenclature

c_p^o	ideal gas specific heat at constant pressure [kJ/kg K, kJ/kmol K]
h	enthalpy [kJ/kg]
h_{fg}	latent heat of vaporization [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
M	molecular mass [kg/kmol]
P	pressure (kPa)
$\dot{Q}$	heat transfer rate [kW]
s	entropy (kJ/kg K)
T	temperature (°C, K)
v	specific volume [m^3/kg]
V	volumetric work output [kJ/m^3]
$\dot{W}$	power [kW]
x	quality
X, Y, Z	generic working fluids

Greek symbols

η_{IHX}	internal heat exchanger effectiveness [%]
η_{p}	pump isentropic efficiency [%]
η_{t}	turbine isentropic efficiency [%]
η	cycle thermal efficiency [%]
Π	integral of ζ over the temperature range $0.6 < Tr < 0.9$, $= \int_{0.6T_c}^{0.9T_c} \zeta \cdot \mathrm{d}T$, see Eq. (12)
ρ	density [kg/m^3]
ω	acentric factor
ζ	any thermodynamic property

Subscripts

0, …,10	thermodynamic state points (Fig. 1)
boil	boiler
c	critical
cond	condenser
est	estimated
f	saturated liquid
g	saturated vapor
−IHX	without internal heat exchanger
+IHX	with internal heat exchanger
max	maximum
net	net
out	outlet
p	pump
r	reduced
ref	reference
sat	saturation
t	turbine
vap	vapor

Acronyms

EoS	equation of state
E%	percent error, see Eq. (11)
FEQ	fundamental Helmholtz equation
IHX	internal heat exchanger
NBP	normal boiling point
ORC	organic Rankine cycle
P-R	Peng-Robinson
RMSE%	root mean square percent error, see Eq. (10)

manufacturers, the sizes as measured by output power, and the types of working fluids. They concluded that the selection of an ORC machine is primarily based on application, source temperature, and required output power.

A number of authors have developed simulation and optimization tools for the analysis of ORC applications. A few of these include Cataldo et al. [5] who studied 41 commonly existing working fluids contained in REFPROP [6] possessing critical temperatures between 100 °C and 300 °C for a low-temperature waste heat recovery ORC application. They used a genetic algorithm to select the optimal working fluids for two heat source inlet temperatures of 100 °C and 150 °C, identifying benzene and Novec649 as the "optimal" working fluids for a source temperature of 100 °C. Victor et al. [7] developed an optimization model to investigate 35 commonly existing single-component working fluids and several binary blends for a low-temperature ORC application where the heat source temperature varied from 100 °C to 250 °C. Their results showed that single-component working fluids yielded higher efficiencies than binary blends. They concluded that their model is a useful tool for selecting the working fluid and the application temperatures. Barbieri et al. [8] developed an ORC simulation model where the thermodynamic properties of the working fluid are calculated from tables generated from experimental pressure-temperature-specific volume data contained in the literature and from ideal gas specific heat values calculated from group contribution methods. They applied their model to six commonly existing working fluids.

In addition to the already mentioned papers, a number of others have focused primarily on a discussion of working fluids appropriate for ORC. While the current paper does not intend to discuss these papers and working fluids in detail, the interested reader is referred to a recent comprehensive review of ORC working fluids by Bao and Zhao [9]. In this paper, the authors reviewed a large number of literature sources and identified 77 commonly existing single-component working fluids and 44 zeotropic blends appearing in the various papers they reviewed. The identified working fluids are all well-described ones, that is, they are ones that are well-characterized by considerable experimental data and/or they are ones for which high accuracy EoS (equations of state) are available.

While there are several tools discussed and used in the literature for calculating the thermophysical properties necessary to investigate ORC performance, two widely used libraries are REFPROP [6] and CoolProp [10]. Each library contains well-characterized, high accuracy EoS for over 100 working fluids. REFPROP [6] is a non-open source program that has been available to the public for some 25 years and is widely used in the refrigeration industry. CoolProp [10] is an open source program with similar capabilities and has been available to the public for the last few years. Both these libraries—and other similar ones—are useful for evaluating well-described working fluids; however, they are unable to evaluate not-so-well-described working fluids (ones where little or no experimental data and/or EoS are available) without a user expending considerable additional effort (time, money, experimentation, and programming). For not-so-well-described working fluids, Brown et al. [11] presented a simple, inexpensive, fast, and sufficiently accurate methodology for engineering purposes for calculating thermodynamic properties and investigating the performance potentials of not-so-well-described working fluids for ORC applications. The methodology of Brown et al. [11] is based on constructing simple cubic EoS [e.g., P-R (Peng-Robinson)] from estimated thermodynamic parameters critical temperature (T_c),

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