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Working fluid charge oriented off-design modeling of a small scale Organic Rankine Cycle system

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ABSTRACT

Organic Rankine Cycle system is one of the most widely used technique for low-grade waste heat recovery. Developing of dynamic Organic Rankine Cycle models played an increasingly important part in system performance prediction. The present paper developed a working fluid charge oriented model for an small scale Organic Rankine Cycle to calculate the theoretical value of working fluid charge level for the system under rated condition. The two heat exchangers are divided into three different zones and related heat transfer correlations are employed to estimate the length variation of each zones. Steady state models have been applied to describe the performance of pump and expander. Afterwards, an overall solution algorithm based on the established model has been proposed in order to exact simulate the system's off-design performance. Additionally, the impact of different working fluid charge volumes has also been discussed. Simulation results clearly shows the variation trend of different zones in both heat exchangers, as well as the variation trend of system operating parameters under various expander output work. Furthermore, the highest thermal efficiency can be reached 6.37% under rated conditions with a working fluid charge volume of 34.6 kg.

1. Introduction

Organic Rankine Cycle (ORC) shows a higher performance for low-grade waste heat recovery than traditional steam-based Rankine cycles. Moreover, due to its high operational stability and structural simplicity, ORCs are more attractive for actual industrial applications. Therefore, researchers have extensively carried out both experimental and theoretical investigations of ORCs in the past two decades or so. Lemmens et al. [1] investigated a 375 kW ORC system used for flue gas heat recovery from an industrial kiln in Flanders, Belgium, and the financial feasibility has been evaluated while taking the specific policy circumstances into account. Budisulistyo et al. [2] discussed a comprehensive design methodology for optimization of organic Rankine cycles using a new design to resource method. The ratio of net power output to the total heat exchanger area is used as the objective function. Amirante et al. [3] presented the recent advances in designing micro steam expanders and gas to gas heat exchangers, which can be effectively used of Organic Rankine Cycle as well as the small combined cycles. Pu et al. [4] conducted experimental study of a small scale Organic Rankine cycle experiment system capable of generating electric power using a low temperature heat source. A single stage axial turbine expander coupled with a permanent magnet synchronous generator was used, where no lubricant oil was used. R245fa and the new environmentally friendly HFE7100 were selected as the working fluids.

Generally speaking, researchers working on ORC systems have made progress in several dimensions. Selection of a suitable working fluid for different kinds of system configurations as well as operating conditions has been one of the core topics of previous researches. Thermodynamic or thermo-economic indicators of components and cycle were evaluated to reveal the effect of physical properties of different working fluids. It is a common choice to set a constant value for the isentropic efficiency of both the pump and expander, as well as the heat transfer coefficient of both the evaporator and condenser. Afterwards, the cycle performance is solved by calculating the relevant thermodynamic steady-states of the T-S diagram. Additionally, the relationship of system's operating conditions and heat source temperature as well as the environmental parameters were discussed. Wang et al. [5] selected nine different pure organic working fluids according to their physical and chemical properties and compared their in the regions when net power outputs were fixed at 10 kW. Dong et al. [6] established a numerical model to investigated the performance of high-temperature Organic Rankine cycle (ORC) with zeotropic mixtures as working fluid. The effects of mixture concentration, temperature gradient of the heat transfer fluid, pinch temperature difference,

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Nomenclature

A	area [m^2]
a	fin length [m]/coefficient [–]
b	fin width [m]/coefficient [–]
C_p	specific heat [kJ/kg K]
d	diameter [m]
E	enhancement factor [–]
F	fin area [m^2]
f	friction factor [–]
g	acceleration due to gravity [m/s^2]
H	fin height [m]
h	enthalpy [kJ/kg]
Ks	surface roughness [–]
K	heat transfer coefficient [W/m^2K]
L	length of pipe [m]
m	mass flow rate [kg/s]
n	fin density [–]
N	suppression factor [–]
N_{rot}	rotating speed [r/min]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
Q	thermal energy [kW]
q	heat flux density [W/m^2]
R	pipe radius [m]
Re	Reynolds number [–]
r	thermal resistance [m^2K/W]
S	spacing [m]
St	Stanton number [–]
T	temperature [K]
W	power [W]
X_{tt}	Lockhard-Martinelli factor [–]
x	the vapor quality [–]

Greek symbols

α	convective heat transfer coefficient [W/m^2K]
α_x	air-bubble coefficient [–]
β	factor [–]
ρ	density [kg/m^3]
μ	viscosity [Pa·s]
ε	efficiency [–]
λ	thermal conductivity [W/m K]
σ	surface tension [N/m]
γ	latent heat [kJ/kg]
δ	fin thickness [m]
u	velocity of flow [m/s]
η	efficiency [–]
Φ	correction factor [–]

Subscripts

amb	ambient
cal	calculated
ch	charge
cond	condensation
cri	critical
e	equivalent
em	electromechanical
ex	exhaust gas
eva	evaporation
f	fin
i	inside
in	inlet
l	liquid
max	maximum
o	outside
out	outlet
pp	pump
pool	pool boiling
r	root
s	swept
su	supply
tp	two-phase flow
v	vapor
w	wall

pressure ratio, and condensation pressure on the first law efficiency have been evaluated. Lu et al. [7] analyzed the internal relation about zeotropic mixture selection under different restrictive conditions such as the fixed condenser bubble temperature, the fixed cooling water temperature rise and the fixed cooling water flow rate. Rajabloo et al. [8] compared thermodynamic performances of the ORC cycle using siloxane mixture as working fluid with the pure fluids in the case of both low and high temperature range. Results indicated that in general the using of siloxane mixture shows a slightly improvement of cycle performance. Recently, many multi-objective functions have been introduced to optimize a given set of desired working conditions. Yang et al. [9] introduced GA (genetic algorithm) to solve the Pareto solution of the thermodynamic performances and economic indicators for maximizing net power output and minimizing total investment cost under diesel engine various operating conditions using six different working fluids. Toffolo et al. [10] provide a method that improves working fluid selection taking into account several criteria at a time considering real cost data and the off-design behavior. This type of simplified modeling is useful as a preliminary design and investigation of the ORC system. In fact, this method provides a useful screening method for the selection of working fluid. However, the physical characteristics and behavior of any real system components somehow remain in a shadow. Therefore, it is not possible to accurately predict the off-design system performance for industrial applications.

System modeling and simulation is another domain of the investigations conducted in the field. Detailed simulation modeling was established for each separate component in an ORC system. Afterwards, the overall cycle model was obtained by connecting the relevant sub-models. Several modeling approaches (both steady-state and dynamic) have been reported in previous literatures. For the evaporator and condenser, a counter flow heat exchanger model can be established by the means of effectiveness-NTU method or LMTD (logarithmic mean temperature difference) method. To exactly predict the heat transfer coefficient, both phase-change heat exchangers were divided into three zones, namely the liquid zone, two-phase zone and vapor zone. Each of them was characterized by proper heat transfer correlations, which can be calibrated based upon the experimental data. Meanwhile, the governing equations for mass, momentum and energy balance can be solved using either the discretization method (based on a finite volume or a finite difference) or the moving boundary model. Jensen [11] proposed a new homogeneous discretized model which assuming the pressure changes to propagate instantaneously, to simulated both heat exchangers dynamic performance. Simulation results of the location of the liquid dry-out front agree well with experimental data giving similar accuracy as the moving boundary models. Vaja [12] proposed the theoretical methods and a full library of dynamic models that can represent the components that usually appear in energy conversion systems based on the Matlab language. Results of this investigation repre-