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Numerical predicting the dynamic behavior of heat exchangers for a small-scale Organic Rankine Cycle

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Abstract

Dynamic modeling is a hot topic for investigations of Organic Rankine Cycle (ORC). In this paper, Moving boundary model and discretized model were used to describe the dynamic behavior of heat exchangers in a small-scale ORC using R123 as working fluid. Overall system model is assembled using dynamic models of heat exchangers combing static models of the scroll expander and the pump. The comparison made between the established models and experimental results shows that both the models can reveal the real system performance sufficiently. Moreover, the moving boundary model is numerically faster than the discretized model, and therefore more suitable for engineering applications.

Keywords: Organic Rankine Cycle (ORC); dynamic simulation; moving boundary model; discretized model

1. Introduction

Organic Rankine Cycle (ORC) system is one of the most widely used technique for low-grade waste heat recovery. ORC's steady state behaviour has been studied by many researchers since more than 20 years ago [1-3]. Recently, developing of dynamic ORC models played an increasingly important part in system performance prediction. From the point of view of dynamic simulation, critical components of an ORC system are the heat exchangers because there are the main heat transfer media and have a time inertia that does not allow for quasi-steady state models as in the turbo-machines such as expander and pump[4-8].

Through the summarization of the previous literatures, two different models were used to describe the dynamic behaviour of heat exchangers, i.e. the moving boundary (MB) model and discretized model (DM) [4,5]. The moving boundary models are low order lumped models particular useful for optimization and control purposes. In this model, the interior of the heat exchanger is divided into three parts: sub-cooled liquid region, two phase region and

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superheated vapor region. On the other side, discretized models based on the balance equations of mass, momentum and energy form an alternative to MB-models when the spatial changes are important. An advantage using discretized models is the possibility of using high accuracy correlations for heat transfer and pressure loss taking the spatial variations into account.

The above-mentioned two models can also be related to ORC simulations. Wei et al. [6] proposed two alternative approaches, which are based on moving boundary and spatially distributed-parameter model, respectively, to be used for the accurate representation of evaporator and condenser's dynamic behaviour in an organic Rankine system. Sun and Li [7] reported a detailed model of an ORC using R134a as the working fluid. A discretized model was applied to the evaporator and condenser. The expander and the pump were modeled with two empirical correlations based on the performance maps provided by the manufacturer. Affinity law was applied to obtain the pump power consumption at different rotational speeds. The optimization results reveal that the relationships between controlled variables and uncontrolled variables are near liner function for maximizing system net power generation and quadratic dependence for maximizing the system thermal efficiency. Quoilin et al. [8] reported a semi-empirical model for a volumetric expander used in a small scale ORC. The model is able to predict the variables of the main characteristics such as the working fluid mass flow rate, the discharge temperature, pressure drop, the internal leakage and the mechanical losses as well as the delivered shaft power. The established model exhibits low good accuracy and robustness.

In general, there is a wide variety of modelling paradigms to estimate the components state in an ORC system, ranging from the simplest method to the most complex one. However, particular attention given to the complete ORC system is rarely found. The present paper proposed an experimentally-validated modelling at system level. Moving boundary model and discretized model are used for describing the two-phase flow model of the heat exchangers. The heat transfer coefficient of each of the three zones in both heat exchangers is determined by relevant heat transfer correlations. To compare the calculation value with the experimental value, two concrete configurations of shell and tube heat exchanger (condenser) and tube-fin heat exchanger (evaporator) are taken into account. Moreover, steady-state models are established for the expander and working fluid pump. The simulation results of the established model must be compared to each other as well as with the experimental results under same operating conditions.

Nomenclature

A	area [m^2]	a	factor
b	factor	e	heat exchanger's effectiveness [-]
h	specific enthalpy [kJ/kg]	m	mass flow rate [kg/s]
N_{rot}	rotating speed [r/min]	P	Pressure [Pa]
Q	thermal energy [kW]	T	temperature [K]
W	system power output [W]		
Greek symbols			
ρ	density [kg/m^3]	η	efficiency [-]
Subscripts			
em	electromechanical	exp	expander
i	inside	pp	pump
r	root	w	wall

2. System description

Fig. 1(a) illustrates the scheme of the considered ORC system. As shown in Figure1, waste heat from the ICE (Internal Combustion Engines) exhaust gas is absorbed by R123 which is used as the working fluid in the evaporator.