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Artificial neural network (ANN) based prediction and optimization of an organic Rankine cycle (ORC) for diesel engine waste heat recovery

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ABSTRACT

This paper presents performance prediction and optimization of an organic Rankine cycle (ORC) for diesel engine waste heat recovery based on artificial neural network (ANN). An ANN based prediction model of the ORC system is established with consideration of mean squared error and correlation coefficient. A test bench of combined diesel engine and ORC waste heat recovery system is developed, and the experimental data used to train and test the proposed ANN model are collected. A genetic algorithm (GA) is also considered in this study to increase prediction accuracy, and the ANN model is evaluated with different learning rates, train functions and parameter settings. A prediction accuracy comparison of the ANN model with and without using GA is presented. The effects of seven key operating parameters on the power output of the ORC system are investigated. Finally, a performance prediction and parametric optimization for the ORC system are conducted based on the proposed ANN model. The results show that prediction error of the ANN model with using the GA is lower than that without using GA. Therefore, it is recommended to optimize the weights of the ANN model with GA for a high prediction accuracy. The proposed ANN model shows a strong learning ability and good generalization performance. Compared to the experimental data, the maximum relative error is less than 5%. The experimental results after optimizing the operating parameters are very close to ANN's predictions, indicating one or more operating parameters can be adjusted to obtain a higher power output during the experiment process.

1. Introduction

With the rapid development of automotive industry, energy saving and emission reduction have become important aspects in recent decades. Generally, a traditional internal combustion (IC) engines can only convert less than 40% of the fuel combustion energy into useful power output. Although many innovative technologies, including gasoline direct injection (GDI), turbo direct injection (TDI), homogeneous charge compression ignition (HCCI), and fuel stratified injection (FSI), have been considered and adopted in recent years, the thermal efficiency of the IC engine has not been improved much. Waste heat recovery is considered to be one of the most promising methods for improving the overall energy conversion efficiency of the IC engine [1,2].

Among various technologies of recovering waste heat from the IC engines, organic Rankine cycle (ORC) has been widely considered because of its outstanding features, such as low initial investment, configuration simplicity, and high efficiency [3–6]. Most of current investigations are mainly focused on the theoretical or thermodynamic analysis [7–11]. Chen et al. designed a novel cascade ORC system, which can recover waste heat from both engine exhaust gas and coolant [12]. Zhao et al. developed a simulation model of diesel engine and ORC combined system and discussed the steady and transient performances of the combined system [13]. Galindo et al. optimized a bottoming ORC system coupled with a gasoline engine from the view point of thermoeconomic and sizing criteria [14]. Yang et al. investigated the economic performance of a transcritical ORC for recovering waste heat from exhaust gas, coolant, scavenge air cooling water and lubricating oil of a large marine diesel engine [15]. Yue et al. proposed two thermodynamic models of a bottoming ORC and diesel engine combined power system and studied the effect on the power output of the proposed models [16].

While thermodynamic analysis of ORC systems has been widely

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Nomenclature

$\dot{V}$	volume flow rate (L/min)
p	pressure (bar)
T	temperature (°C)
Tor	torque (N m)
$\dot{W}$	power (kW)
w	weight
b	bias

Subscripts

exp	expander
con	condenser
p	pump
in	inlet
out	outlet
h	hidden layer
o	output layer

Acronyms

ORC	organic Rankine cycle
ANN	artificial neural network
GA	genetic algorithm
GDI	gasoline direct injection
TDI	turbo direct injection
HCCI	homogeneous charge compression ignition
FSI	fuel stratified injection
BP	back propagation
MSE	mean squared error
R	correlation coefficient

performed, some researchers have investigated its performance experimentally. It has been realized that although the whole ORC system, mainly including five components, is not complex, achieving an theoretical power output for a small scale ORC system experimentally is difficult and challenging [17,18]. One of the main barriers is due to the technical limitation of kW-scale expanders [19–21] and some research works have been conducted to understand/address such issues through experimentally studies. Zhang et al. developed an ORC-based experimental system to recover exhaust waste heat from a diesel engine with a single screw expander [22]. Their results indicated that the maximum power output of 15 kW using an ORC system can be achieved at a diesel engine rated condition of 250 kW. Shu et al. constructed a thermal oil storage/ORC system for exhaust waste heat recovery from a 240 kW diesel engine [23]. In their study, the expander was replaced by an expansion valve to estimate the potential power output. Galindo et al. evaluated the effect of adding an ORC waste heat recovery system on a turbocharged gasoline engine and showed that the maximum power output of 1.83 kW could be achieved using a swash-plate expander [24].

Gaps between theoretical and experimental studies are not only present in the area of ORC-based heat recovery, but also in many thermal energy engineering fields. Many researchers have tried to fill this gap by adopting new modeling techniques that can predict system performance in more accurate manners. In recent years, the artificial neural network (ANN) method has been widely adopted in the field of thermal energy engineering for design and performance optimization because of the advantages of self-adaption, self-learning, nonlinear mapping and fault tolerance. Li et al. compared three different types of ANN models for wind speed forecast [25]. Zhao et al. designed and trained an ANN model to optimize the geometrical compression ratio and operating parameters of an Atkinson cycle engine [26]. Boukelia et al. presented an optimization of a parabolic trough solar thermal power plant based on a feed-forward back-propagation ANN model [27]. Arslan et al. proposed an ANN model for the evaluation of a supercritical ORC-Binary geothermal power system by considering various learning algorithms [28]. Rashidi et al. investigated the thermodynamic performance of an ejector refrigeration cycle using an ANN method [29].

As briefly discussed above, the current literature shows that the experimental results from many ORC studies are far from theoretical values [23,30]. Most of the thermodynamic models cannot provide accurate transient predictions of the ORC system behavior [18,23]. This is due to the fact that no pressure drops, heat losses and other factors affecting the actual system performance are considered in most of the thermodynamic models. The isentropic efficiencies of the expander and pump are usually kept at a constant value, and the whole system is assumed to be under steady state. Even for a simple ORC configuration that includes five main components (i.e., evaporator, expander, condenser, reservoir, and pump), performance with various component designs and operating conditions may not be accurately predicted because of nonlinear behaviors. Therefore, improving the modeling accuracy of ORC system is a critical path to determine optimal system configurations and control strategies in more precise and reliable manner. To address this challenge, this study proposes an ANN-based model to predict and optimize the transient performance of the ORC system for IC engine exhaust waste recovery. Artificial neural network, as a nonlinear modeling tool, is inspired by the biological neural networks. To the best of our knowledge, there is currently no existing ANN-based ORC models that are established for IC engine waste heat recovery. Furthermore, at the present time there is a lack of valid experimental data for IC engine waste heat recovery based on ORC system. We authors would like to open a broad range of possibilities for system performance prediction and optimization and try different methods of improving as high as possible the prediction accuracy for the transient performance of the ORC system. In this paper, a test bench of combined diesel engine and ORC waste heat recovery system is developed first to generate the experimental data used to train and test the ANN model. A genetic algorithm (GA) is also considered in this study to increase prediction accuracy, and the ANN model is evaluated with different learning rates, train functions and parameter settings. Then an ANN based prediction model of the ORC system incorporated with GA is established and a prediction accuracy comparison of the ANN model with and without using GA is presented. The effects of key operating parameters are further investigated using the proposed ANN model. Finally, a performance prediction and parametric optimization for the ORC system are conducted based on the proposed ANN model.

2. Test bench of waste heat recovery system

The schematic diagram of the waste heat recovery system is shown in Fig. 1. It can be seen that the whole waste heat recovery system consists of two subsystems including a diesel engine and an ORC system.

2.1. Test bench of diesel engine

In this study, exhaust gas discharged from an in-line six cylinder heavy duty diesel engine is the waste heat source for the ORC system. The main technical parameters of the diesel engine are listed in Table 1. An eddy current dynamometer is coupled with the diesel engine to control engine load. Experimental data is collected by the dynamometer control system. The test bench of the diesel engine is shown in Fig. 2. An exhaust port of the diesel engine is connected with an evaporator by bellows. Exhaust gas, after exchanging heat with working fluid in the

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