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Integrated simulation and control strategy of the diesel engine–organic Rankine cycle (ORC) combined system

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ABSTRACT

The organic Rankine cycle (ORC) is regarded as one of the most promising methods to increase the efficiency of diesel engines. Owing to the variability of exhaust energy with engine speed and load, the ORC should be designed for various operating conditions of engines for optimal waste heat recovery (WHR). In this study, an integrated simulation model of the diesel engine–ORC combined system (the combined system) is built by GT-Suite. Based on the model, the MAPs of optimum parameters are obtained by an artificial neural network (ANN) and a genetic algorithm (GA). Subsequently, operation modes of the combined system under various conditions are proposed. Finally, a control strategy of switching operation modes and adjusting parameters that adapts to various conditions of diesel engines is developed by GT-Suite and MATLAB/Simulink. Simulation results show that the optimum pump speed is steady approximately 1000 r/min under the low load region of the engine and increases with the engine load when the engine speed is higher than 1800 r/min. By contrast, the optimum expander speed is 1500 r/min in all selected engine operating conditions. Further investigations indicate that the performance of the combined system presents improvements, with a 3.57% increase in thermal efficiency and a 10.09 g/(kW·h) reduction in brake specific fuel consumption (BSFC) when compared against the original diesel engine. These preliminary results prove that the integrated simulation model can be used for further research. Meanwhile, with regard to the proposed control strategy, more thorough experimental research needs to be conducted.

1. Introduction

The thermal efficiency of engines has been greatly improved through time. However, according to the heat balance of the engine, about one-third of the total energy from fuel combustion is still wasted as exhaust gas, which not only aggravates the energy crisis of fossil fuels but also causes serious environmental pollution [1]. Therefore, the efficient reuse of waste heat is an effective way to improve thermal efficiency and reduce the fuel consumption and pollutant emissions of the engine [2–4]. The organic Rankine cycle (ORC) system with a high percentage of waste heat recovery (WHR) from an engine attracts widespread interest [5–7]. A review of literature in the past decades revealed that three methods were used in investigations of the ORC system for the WHR of engines, namely theoretical analyses, experimental research, and numerical simulations.

1.1. Theoretical analyses

Theoretical analyses based on the first and second laws of thermodynamics have contributed significantly to the improving performance of the ORC system. System configurations of the ORC system have been designed for different heat sources of engines, such as exhaust gas, coolant, exhaust gas recirculation cooler, and charge air cooler. Wang et al. presented a dual-loop ORC, which consists of a high temperature loop that recovers the exhaust waste heat and a low temperature loop designed to recover the coolant waste heat. The results showed that the effective thermal efficiency increases by a maximum of 8% over the engine's entire operational range [8]. Dolz et al. evaluated the different theoretical bottoming Rankine cycle configurations applied as a WHR system. Their study indicated that the configuration with high temperature heat sources is more realistic [9]. Many researchers have performed a comparative analysis of wet, isentropic, dry and mixed working fluids. Hung et al. found that the system efficiency increases and decreases for wet and dry working fluids respectively, and the

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Nomenclature

c_p	specific heat at constant pressure (kJ/kg·K)
D	character length (m)
d	diameter of tube (m)
E	parameter of Friedel
F	parameter of Friedel
f	friction coefficient
G_{tp}	total mass velocity of liquid plus vapor
g	acceleration due to gravity (m/s^2)
H	parameter of Friedel
Δh	enthalpy changes (kJ/kg)
L	length of tube (m)
$\dot{m}$	mass flow rate (kg/s)
N	speed (r/min)
n	rotational speed (r/min)
dP/dL	frictional pressure gradient (Pa/m)
ΔP	friction pressure drop (Pa)
$\dot{Q}$	heat transfer rate (kW)
T	temperature (K)
U	factor in Eq. (12) (Pa/m)
V_{disp}	displacement
$\dot{W}$	power (kW)
x	vapor quality

Greek letters

ρ	mass density (kg/m^3)
μ	dynamic viscosity (N·s/m^2)
σ	surface tension (N/m)
η	efficiency (%)
η_v	volumetric efficiency

Dimensionless numbers

Fr	Froude number
Re	Reynolds number
We	Weber number

Subscript

1	liquid
b	back pressure
com	combined system
disp	displacement
en	engine
ex	expander
fric	friction
g	vapor
ise	isentropic
n	net
out	outlet
p	pump
tp	two-phase

Acronyms

ANN	artificial neural network
BSFC	brake specific fuel consumption
CFD	computational fluid dynamics
GA	genetic algorithm
ORC	organic Rankine cycle
WHR	waste heat recovery

isentropic working fluid achieves an approximately constant value for high turbine inlet temperatures. Their study indicated that the isentropic working fluid is most suitable for recovering low-temperature waste heat [10]. Wang et al. investigated nine organic working fluids and found that R245fa and R245ca are the most suitable working fluids for an engine WHR application [11]. As a closed system, the ORC system is mainly affected by some parameters. Thus, some scholars use a variety of optimization algorithms to optimize the operating parameters. Hatami et al. used artificial neural network (ANN) and genetic algorithm (GA) to obtain the optimized geometry for a finned-tube heat exchanger. They showed that the average efficiency of the heat exchanger is about 8% [12]. Xiao et al. optimized the evaporation and condensation temperatures for subcritical ORC by the method of linear weighted evaluation function. The results illustrated that the multi-objective optimization of ORC shows superiority to the single-objective optimization [13].

1.2. Experimental research

Experimental research of the ORC system is of great importance for its design and application. Most of the current experimental research is focused on key components, including pump and expander. Guillaume et al. experimentally compared the performance of an ORC system equipped with a radial-inflow turbine for two working fluids. The results showed the importance of the expander built-in volume ratio to each specific application [14]. In particular, some experimental studies demonstrated that scroll expanders show very promising results [15,16]. Quoilin et al. indicated that the power consumption of the pump should be considered in the calculations of thermal efficiency and net power of ORC systems [17]. Meng et al. constructed a test bench of a multistage centrifugal pump using R123 as working fluid. The results showed that the pump efficiency is between 15% and 65.7% in an ORC system environment for WHR of engines [18]. Lei et al. studied a Roto-Jet pump in a small scale ORC system, and built an experimental system to test its performances in simulative ORC conditions. The results showed that the efficiency of the pump is between 11% and 23%, and increasing the rotational speed of the pump or reducing the flow rate leads to a general decrease of pump efficiency in the parametric ranges under study [19].

1.3. Numerical simulations

For application, detailed dimensions and structural characteristics of the components of the ORC should be emphasized. On the contrary, theoretical analyses are mainly studied under the preset assumptions, without considering the detailed dimensions and structural characteristics of the components [20]. Experimental research also has limitations, such as long development cycle, large investment and high design cost. Therefore, numerical simulations, which can quickly carry out the relevant design and obtain reliable results based on a large number of experimental data and theoretical analysis, are preferred by many researchers. Wang qualitatively analyzed the thermal-hydraulic characteristics of a fin-and-tube evaporator for engine WHR using the computational fluid dynamics (CFD) method and synergy principle. The simulation results showed that the exhaust on the shell side flows primarily in parallel with the fin layers [21]. Zhang et al. created a detailed 3D simulation model on flow and heat transfer in the shell side of the whole heat exchanger with helical baffles by using the FLUENT with the grid systems being generated by GAMBIT [22,23]. However, obtaining more reliable simulation results for application to the WHR of engines has specific challenges.

First, the variability of engine speed and load usually causes the