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Performance evaluation of free piston compressor coupling organic Rankine cycle under different operating conditions

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ABSTRACT

An organic Rankine cycle coupling free piston compressor (ORC-FPC) system has been proposed, which is used in recovering the waste heat of exhaust gas from the stationary compressed nature gas (CNG) fueled internal combustion compressor. The free piston compressor functions as an expander in ORC and operates reciprocally to compress natural gas in compression cylinders to demanded pressure. After capturing the waste heat available and turning into vapor in evaporator, the working fluid R245ca can provide power to drive the free piston moving reciprocally in expander. The model of ORC-FPC built up in the GT-suite ver. 7.0 assists evaluating performances of this system under different operating conditions. In this paper, the operating condition includes two aspects: thermodynamic state of working fluid and input power. The purpose of simulation based on the model is to specify appropriate thermodynamic states of working fluid which yield high value of η (the ratio of work produced by the power piston to enthalpy reduction of working fluid in the power cylinder) and k (the ratio of output CNG's mass to enthalpy reduction of working fluid in the power cylinder) value. Performances of the ORC-FPC under different input power, which determined by the operating frequency and injection quantity of the heated working fluid, have also been evaluated.

Results show that when the heated working fluid is at 11.5 bar and 383 K, the system achieves better performances than other thermodynamic states, of which k is 601.1 mg/kJ and η is 44.3%. Based on the optimum thermodynamic state and the principle of obtaining the maximum k, the specific input power determined by $\dot{m}$ (332 g/cycle) and T_{cyl} (1.2 s/cycle) can make the system achieve better performances, of which k is 648.9 mg/kJ and η is 42.8%. Performances prediction in the real system based on the simulation results has been evaluated in this paper for its intended application. Through calculation and rational analysis, the compressing ability of ORC-FPC in real-world can reach 9.04 L/s and its actual size can be increased based on the required compressing capability of the final application.

1. Introduction

Sustainable energy utilization and environment protection are important aspects in sustainable development. But in China, the problem of environment pollution is increasingly serious as a result of the high consumption of different kinds of energy resources [1,2], most of which are in the situation of being utilized seldom or wasted seriously [3]. In order to settle these problems and maintain the healthy development of economy and society, it is necessary for Chinese government to develop low-carbon economy and adopt clean energy to meet international community's requirement on environment change [4]. Compared to the severe air pollutions from coal-fired power plants [5–7], power plant that use natural gas (NG) as fuel produces much less emissions, such as CO2, NOX and SO2 [8]. Hence, the consumption of NG, which is cleaner and suitable for the development of the low-carbon economy, is increasing gradually with the support of the West-to-East Natural Gas Transportation Project in China. According to the research made by Li et al. [9], natural gas will become an important substitute for coal in some parts of the Chinese primary energy consumption. However, the concentrated distribution of the richer natural gas makes it difficult for long-distance gas transport [10]. Therefore, natural gas from the gas field should be compressed to high pressure before transporting a long distance through the pipeline. The compressing process of NG is finished in the stationary gas-fired internal combustion compressor, accompanying a large quantity of heat from exhaust gas is discharged into the atmosphere. As the heat energy cannot be used fully, the efficiency of the stationary compressor is in a

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Nomenclature

ΔH	total enthalpy reduction (J)
H_{left_in}	enthalpy of working fluid flow into the left chamber of power cylinder(J)
H_{right_in}	enthalpy of working fluid flow into the right chamber of power cylinder(J)
H_{init}	initial enthalpy of the power cylinder (J)
H_{out}	enthalpy of working fluid flow out of the power cylinder (J)
H_{detain}	detained enthalpy of the power cylinder (J)
H_e	outlet enthalpy of the power cylinder (J)
H_i	inlet enthalpy of the power cylinder (J)
W	the output work of the power cylinder(J)
W_{left}	output work of the power cylinder's left chamber (J)
W_{right}	output work of the power cylinder's right chamber (J)
Δm	output CNG's mass of two compression cylinders (mg)
$\dot{m}$	injection quantity of heated working fluid in one cycle (g/cycle)
T_{cyl}	time that the power piston takes to operate in one cycle (s/cycle)
f	operating frequency of the free piston (cycle/s)
Q_p	heat dissipation of power cylinder (J)
Q	total heat release of the system (J)
P_{in}	input power (W)
h	specific enthalpy (J/g)
ST	saturation temperature (K)
ST-5	temperature that 5 K lower than the saturation temperature (K)
c	damping coefficient
v	velocity of the power cylinder(m/s)
v_e	outlet velocity of working fluid (m/s)
v_i	inlet velocity of working fluid (m/s)
Z_e	outlet height of working fluid (m)
Z_i	inlet height of working fluid (m)
L	linear displacement (m)
F_f	friction force on the power piston (N)
W_f	friction work loss (J)
W_c	work of two compression cylinders (J)

Greek letters

η	work efficiency of the power cylinder
k	the ratio of output CNG's mass to enthalpy reduction of working fluid (mg/kJ)

Abbreviation

ORC	organic Rankine cycle
FPC	free piston compressor
CNG	compressed natural gas
NG	natural gas
WF	working fluid
HT	high temperature
HP	high pressure
LDC	left dead center
RDC	right dead center

low level. Aim at making full use of the heat energy from exhaust gas and improving efficiency of the stationary compressor, a free piston compressor based on organic Rankine cycle, which assists the stationary compressor in compressing natural gas, is proposed in this paper.

Owing to its great flexibility and high reliability, the organic Rankine cycle (ORC) has been widely used in the field of low-grade energy recovery. Coupling with the ORC, different power plants has been designed to recover the low-grade energy from industrial waste heat [11,12], solar energy [13] and geothermal energy [14,15], reducing the energy loss and improving system efficiency.

Many prior research efforts have been made to study the performance and optimization of the ORC. Kaska [16] analyzed the efficiency of ORC from the perspective of energy and exergy. His result showed that evaporation pressure and pinch-point had significant effect on both energy and exergy efficiencies. Muñoz de Escalona et al. [17] analyzed part-load performances of gas turbine combined with an ORC bottoming cycle and studied influence of different control strategies on the system. The paper confirmed the interest of merging gas turbines and ORC units for efficient power generation under variable operating conditions and proposed the real potential of state-of-the-art technology in the application. Khatita et al. [18] utilized the ORC in an existing gas treatment plant to recover the waste heat and convert it into electricity. They built up simulation model to study influence of two different cycles (the basic and the regenerative cycles) on the system, and then select the more suitable parameters for the system based on simulation results. Farrokhia et al. [19] presented the preliminary results of an experimental investigation of a natural gas-fired micro-CHP system for residential buildings based on an organic Rankine cycle (ORC). Experiments were performed to obtain the heat source temperature of the maximum electrical power output. Dai et al. [20] examined effects of different working fluids and their thermodynamic parameters on the ORC performance by means of the genetic algorithm. Results showed that the working fluid with non-positive saturation vapor curve slope had the best performance property to the cycle.

Apart from these previous researches conducted about performances of the ORC influenced by different factors, the ORC has also been widely used in the related field of natural gas. Yan et al. [21] integrated an SOFC-GT system with an ORC using liquefied natural gas as heat sink to recover the cryogenic energy of LNG. Their result based on the mathematical model indicated that some key thermodynamic parameters had important influence on net power output and electrical efficiency. Kostowskia et al. [22] integrated an internal combustion engine (ICE) with an organic Rankine cycle (ORC) to evaluate the recovery system for natural gas expansion from the view of energy and exergy. Results indicated that the natural gas expansion coupling the ORC could enhance the efficiency of gas pressure reduction stations.

Moreover, researches focused on different expanders have been conducted in recent years. Clemente et al. [23] analyzed energy efficiency of organic Rankine cycles with scroll expanders and built the detailed model of the scroll machine to calculate the performances of both a compressor and an expander. Antonelli et al. [24] selected a rotary expander in the ORC for generating electricity. They developed numerical model of the expansion device with the simulation tool AMESim v.12 and used the simulation of this machine for the evaluation of delivered power, isentropic efficiency and specific working fluid consumption. Qiu et al. [25] discussed the selection and choices of the expanders for ORC-based micro-CHP systems. They introduced and evaluated the working principles and the characteristics of several kinds of expanders, including turbine expanders, screw expanders, scroll expanders and vane expanders. In this paper, a reciprocal free piston compressor which works as the expander in the ORC has been presented in detail. Comparing with above expanders in the ORC, the free piston expander has many advantages, such as less moving parts, a simple structure and less mechanical loss.