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Feasibility analysis and performance characteristics investigation of spatial recuperative expander based on organic Rankine cycle for waste heat recovery

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ABSTRACT

This paper proposes a new concept of spatial recuperative expander which injects cold refrigerant during exhaust stroke as a measure of direct contact heat transfer. The commercial simulation tool GT-SUIT 7.4 is employed to model and verify the feasibility of spatial recuperative expander. The research contents are comprised of the following aspects: Firstly, the principles and performance characteristics between traditional reciprocating piston expander and spatial recuperative expander have been investigated. Secondly, the potential of spatial recuperation by adjusting cold refrigerant injection timing has been studied. Thirdly, the relation between expander performance and variable expansion ratio under constant operating condition has been discussed. Fourthly, the thermodynamic performance of spatial recuperative expander under various operating conditions has been examined. The simulation results indicate that: Firstly, the torque per unit mass, thermal efficiency, exergetic efficiency, isentropic efficiency and recuperative efficiency of optimum spatial recuperative expander are 51.00%, 6.74%, 20.79%, 5.68% and 11.36% higher than traditional reciprocating piston expander respectively. Secondly, the cold refrigerant injection timing has little influence on recuperative efficiency because the recuperation process can complete within 16.67 ms. Thirdly, different operating conditions correspond to particular optimal expansion ratio. Fourthly, increasing the pump pressure and maintaining appropriate superheated degree can reconcile both power output and thermal economy. While increasing the refrigerant temperature and preserving suitable pump pressure could benefit both recuperative performance and power output.

1. Introduction

Low and mediate grade waste heat which reject from conventional thermal power plant, metallurgical plant, cement plant should be utilized efficiently by various technologies, such as turbocompounds, Rankine cycle (RC)/organic Rankine cycle (ORC), combined heat and power (CHP) and thermoelectric generators. Particularly, ORC is an effective measure to recover low grade waste heat for high efficiency and reliability. The selection of heat source, cold sink, refrigerant, types and parameters of expander are the critical task in constructing the entire ORC system [1].

Expander exerts a strong influence on ORC efficiency besides working fluid properties [2–4] because it is the convertor that transforms thermal energy into mechanical work. Generally, the expander types can broadly divide into five categories: (1) reciprocating piston expander, (2) turbine expander, (3) scroll expander, (4) rotary vane expander, (5) swash plate expander. All of them belong to displacement expander except turbine expander.

From the first category, reciprocating piston expander is more suitable for on-road vehicle because exhaust temperature usually undergoes wide range fluctuation. Reciprocating piston expander could achieve high expansion ratio to elevate power output and thermal efficiency. Furthermore, it could tolerate droplets formation during expansion process which is superior to impulse turbine [1,5–7]. Yun et al. [8] investigated the effect of arranging two expanders in parallel to enhance the system flexibility for heat source variation. They alleged that parallel expander used in ORC (PE-ORC) has a potential to obtain higher power output and thermal efficiency than traditional ORC configuration. Daccord et al. [1] developed an axial piston expander free of oil lubrication and built the relevant expander test bench. They declared that oil-free axial piston expander is capable of dealing with droplets even under high expansion ratio (>12). They also certified that expander performance enhances with increasing expansion ratio.

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Nomenclature

c_p	specific heat at constant pressure (kJ/(kg K))
c_v	specific heat at constant volume (kJ/(kg K))
D	cylinder diameter (mm)
$\dot{E}_{x,hot}$	the exergy rate of hot refrigerant (kJ/s)
$h_{hot,0}$	specific enthalpy of hot refrigerant if it was cooled down to the ambient temperature (kJ/kg)
$h_{hot,1}$	specific enthalpy of hot refrigerant (kJ/kg)
$h_{cold,2}$	specific enthalpy of cold refrigerant (kJ/kg)
$h_{out,3}$	specific enthalpy of outlet refrigerant (kJ/kg)
$h_{out,3s}$	specific enthalpy of outlet refrigerant after undergoing an isentropic expansion process (kJ/kg)
L	connecting rod length (mm)
m_{hot}	the integrated mass flow rate of hot refrigerant (kg)
$\dot{m}_{hot,1}$	mass flow rate of hot refrigerant (kg/s)
$\dot{m}_{cold,2}$	mass flow rate of cold refrigerant (kg/s)
P_{output}	average power output per cycle (kW)
$\dot{Q}_{hot,1}$	the heat delivered by hot refrigerant in the expander (kJ/kg)
$\dot{Q}_{rec}$	the recuperative thermal energy (kJ/kg)
R	crank radius (mm)
S	stroke (mm)
$s_{hot,0}$	specific entropy of hot refrigerant if it was cooled down to the ambient temperature (kJ/(kg K))
$s_{hot,1}$	specific entropy of hot refrigerant at expander inlet end (kJ/(kg K))
T_0	ambient temperature (K)
T_{tq}	average torque per cycle (N m)
$T_{tq,per\ unit\ mass}$	torque per unit mass (N m/kg)
V_0	clearance volume (L)
X	piston position (mm)

Greek letters

α	hot refrigerant injection timing (°CA)
μ	the ratio of crank radius to connecting rod length
ρ	expansion ratio
η_{ex}	expander exergetic efficiency
$\eta_{is,expander}$	the isentropic efficiency of expander
η_{rec}	expander recuperative efficiency
η_{th}	expander thermal efficiency

Abbreviations

CHP	combined heat and power
ORC	organic Rankine cycle
PE-ORC	parallel expander used in organic Rankine cycle
RC	Rankine cycle

Even though conventional piston expanders have made enormous strides in the last few years, researchers still put forth some innovative ideas. For example, Chiong et al. [9] presented a new concept of expansion device which adopts nozzle as a portion of secondary steam cycle. They announced that nozzle piston expander has the potential to increase the power output up to 4.75 kW which is nearly seven times higher than conventional expander.

From the second category, impulse turbine has attracted extensive attention due to its high isentropic efficiency and compact design for optimum utilization of space [10,11]. However it cannot bear droplet formation during expansion process which largely constraints thermal efficiency improving [4,12]. Turbine is generally adopted as expander in large-scale Rankine cycle systems [13]. From the third category, scroll expander is also one of the popular expansion devices which usually acts as turbine alternative in small and micro ORC. Because it has relatively high efficiency and the capacity to tolerate droplets [13–15]. However, the low expansion ratio (<5) in a single stage leads to a poor power output [16]. From the fourth category, there are some important advantages of vane expander: high gravimetric specific power, adaptable to wet gas condition and cost effective [17,18]. However, there are no ORC-dedicated vane expanders available. Modified and specially adapted vane expanders are often applied as expansion device in small scale ORC systems [17]. From the fifth category, Galindo et al. [19] investigated the physical parameters influence of the swash-plate expander prototype. They indicated that the real Rankine cycle efficiency is two thirds lower than the maximum theoretical efficiency. However, the major researches about swash-plate expander are still under theoretical investigation. It would take quite a long time to construct mature technique and stable products quality.

In summary, reciprocating piston expander is particularly suitable for automotive waste heat recovery and its advantages list as below:

1. Both high power output and thermal efficiency thanks to high expansion ratio (>12).
2. The capacity to handle droplet.
3. Suitable for low mass flow rate.
4. Low and mediate operating speed (<3000 rpm).
5. A simple design and sealing due to relatively low gas pressure and rotational speed.

As a result, piston expander would be adopted as the main research subject in this paper.

As is well known, adopting recuperator or preheater in ORC system would help improve cycle efficiency and reduce the load of evaporator [20–23]. Yekoladio et al. [20] considered four types of configurations including basic ORC, recuperative ORC, regenerative ORC and regenerative couple recuperative ORC. They claimed that the large temperature difference between heat source and working fluid would cause considerable exergetic destruction. In other words, the various levels of heat source should be utilized at appropriate stages in ORC system. Hence, both recuperation and regeneration are usually taken into consideration in actual application. However, this would increase the system complexity and cost correspondingly which hinders the extensive use in automobile. So it is necessary to simplify the construction of ORC system.

This paper presents a spatial recuperative expander to perform waste heat recovery from exhaust. The simulation model is established and verified by software GT-SUITE 7.4. The framework of this paper is shown in Fig. 1.

The main contributions of this work list as follows:

1. A new concept of spatial recuperative expander with variable expansion ratio for waste heat recovery has been presented.
2. The power output, thermal economy as well as recuperative performance of spatial recuperative expander under various operating conditions have been investigated.
3. A comprehensive comparison between spatial recuperative expander and traditional reciprocating piston expander has been carried out.
4. Comparative study shows that spatial recuperative expander can achieve better power output and energy conversion efficiency than traditional reciprocating piston expander.