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A study of clearance height on the performance of single-screw expanders in small-scale organic Rankine cycles

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ABSTRACT

A single-screw expander (SSE) is a type of volumetric expander that can be applied to low-grade heat and waste heat recovery utilizing the organic Rankine cycle system. In this paper, a new thermodynamic modeling of SSEs considering the friction power consumption is carried out to examine the performance. The mathematical model was verified by experimental results, and the calculation results have a good agreement with the experimental results. The clearance height has great influence on the expander performance. The influence of clearance height on the leakage flow rate, friction power consumption, volumetric and isentropic efficiency were investigated. Results show that path L_8, L_7 and L_{2+4} are the three main leakage paths, and path L_8, L_7 and L_9 are the three main friction power consumption. Compared with the meshing clearance height, the fitting clearance has a more significant effect on the performance of SSEs. Setting a higher fitting clearance and meshing clearance is an effective measure to reduce friction power consumption and prevent gaterotor wear, respectively. It would be favorable if the fitting and meshing clearance height is no less than 0.04 mm and 0.02 mm, respectively.

1. Introduction

Low grade heat and industrial waste heat recovery through organic Rankine cycle (ORC) systems is regarded as one of the most promising eco-friendly energy-saving technologies. Current ORC research mainly focuses on the selection of working fluids [1–3], optimization and analysis of ORC systems [4–7], and expander performance, which is a key component of the ORC system [8–11].

Volumetric expanders offer the following advantages over turbines in the low power range: high pressure ratio, high efficiency, low rotational speed, and tolerance of the two-phase flow [9]. The volumetric expander market is not mature yet, and only a few commercial volumetric expanders are available for waste heat recovery systems, such as scroll and screw expanders [10]. Ziviani et al. [12] compared a scroll and a single-screw expander (SSE) for low temperature ORC systems in residential applications. The said researchers concluded that the SSE presents a higher power output and leads to higher ORC overall efficiency despite a lower maximum value of the isentropic efficiency because of the limited expansion ratio. The SSE can be widely used in the ORC systems.

Some research has been done in SSE used in ORC system. A SSE with 155 mm diameter screw has been built by Zhang et al. [13], which is for ORC system of waste heat recovery from exhaust of diesel engine. The maximum values of volumetric efficiency, adiabatic efficiency and power output of single-screw expander are 90.73%, 73.25% and 10.38 kW, respectively. An experimental characterization of SSE utilizing SES36 as the working fluid was presented by Desideri et al. [14]. The maximum expander isentropic efficiency and generated power were 64.78% and 7.8 kW, respectively. Ziviani et al. [15,16] studied a small-scale ORC unit for waste heat recovery by employing two working fluids, i.e., SES36and R245fa. The maximum overall isentropic efficiency of 64.7% was achieved with SES36 [15] and the ORC system running with SES36 presented the maximizing expander efficiency and system performance for a pressure ratio between 7 and 9 [16]. R245fa led to 10% higher power output but the expander maximum isentropic efficiency was 17% lower [16]. Lei et al. [17] carried out experiments to analyze the characteristics of the developed single screw expander and the ORC system using R123 as the working fluid. The maximum

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Nomenclature

Variables

A	central distance between the screw and gaterotor [m]
b	width of the gaterotor teeth [m] width of the leakage path [m]
C	flow coefficient
c_f	speed of fluid [m/s]
c_l	specific heat of oil [J/(kg·K)]
d_g	equivalent diameter [m]
E	energy [J]
f	slip factor
g	acceleration of gravity [m/s^2]
h	specific enthalpy[J/kg]
i	gear ratio
L	leakage path length [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
N	number of screw grooves
n	rotational speed [rpm]
p	pressure [Pa]
Q	heat transfer quantity[J]
r	radius [m]
S	area [m^2]
T	temperature [K]
U	internal energy[J]
u	specific internal energy[J/kg]
V	volume [m^3]
v	specific volume[m^3/kg]
W	work [J]
w	rotation angle speed [rad/s]
z	height [m]

Greeks

α	void fraction
θ	rotation angle [rad, °]
λ	heat conductivity
μ	dynamic viscosity
η	efficiency
ρ	working fluid density [kg/m^3]
κ	heat convection coefficient
τ_f	viscous force
ε	expansion ratio
δ	clearance height [m]
χ	ratio of gas in the gas-oil mixture

Subscripts

1	screw
2	gaterotor
CV	control volume
d	discharge
f	friction
g	gas
i	internal or the i_{th} leakage path
iso	isentropic
in	fluid enter the control volume
k	kinetic
l	lubricating oil
lea	leakage
out	fluid leave the control volume
p	potential
$real$	actual value
s	suction
sh	shaft
th	theoretical value
v	volumetric

expander shaft power, shaft efficiency, isentropic efficiency, volumetric efficiency and expansion ratio were 8.35 kW, 56%, 73%, 83% and 8.5, respectively. Giuffrida et al. [18] built a semi-empirical modelling of a SSE for small scale ORC to analyze the expander performance based on variations of the operating conditions. Furthermore, some experimental research has been done in SSE employing compressed air as the working fluid. Wang et al. [19] tested and discussed three SSE prototypes with different gaps and the experimental results indicated the prototype with medium gap had the best overall performance, which the volumetric efficiency and shaft efficiency is 66% and 60%, respectively. Xia et al. [20] investigated the performance of this prototype with different inlet vapor dryness. The results indicated that with the increase of inlet vapor dryness, the power output and expansion ratio were increased, but the volumetric efficiency were decreased. Lu et al. [21] tested an SSE utilizing a compressed air refrigeration system and obtained an adiabatic efficiency above 65%.

Although much research has been devoted to the SSE, limited work has been done on clearance height of SSE in details. The clearance between the screw, gaterotor and shell is inevitable for the safe and reliable operation of SSEs. Due to the pressure difference, the working fluid can leak from one chamber to the neighboring chamber or the discharge chamber through the clearance, which are very important factors to the mass flow rate and efficiency of SSEs. Moreover, friction power consumption exists when there is relative motion in the clearance. Therefore, the clearance height has great influence on the performance of SSEs and should be investigated in details.

In this paper, a new thermodynamic model of SSEs considering the friction power consumption is carried out to examine the performance. In order to verify the mathematical model, the calculation results have been compared with the results of the experiment carried out by Lei et al. [17], in which the important structure parameters used for simulation study are given. And the performance of the SSE is evaluated under different rotation speed and expansion ratio. Then the leakage flow rate and the friction power consumption of each leakage path are analyzed. The influence of clearance height on the leakage flow rate, friction power consumption, volumetric and isentropic efficiency are investigated.

2. Thermodynamic model of the SSE

2.1. Mass balance equation

As shown in Fig. 1, the control volume of the SSE is formed by the screw groove, profile surfaces of the gaterotor teeth, and inside wall of the shell. Based on the mass balance, the change of mass in the control volume can be expressed as:

$$\frac{\mathrm{d}m}{\mathrm{d}\theta_1} = \sum \frac{\mathrm{d}m_{in}}{\mathrm{d}\theta_1} - \sum \frac{\mathrm{d}m_{out}}{\mathrm{d}\theta_1} \tag{1}$$

where m is the mass flow rate in the screw groove, and m_{in} is the fluid enter and leak in the control volume and m_{out} is the fluid discharge and leaked out of the control volume. During the intake process, m_{in} considering the air intake loss can be calculated by the