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Experimental investigation and modeling of a hermetic scroll expander

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HIGHLIGHTS

- An experimental investigation of a lubricated hermetic scroll expander derived from compressor.
- A semi-empirical steady-state model is developed on the basis of the experimental data.
- The investigated expander reaches promising net efficiencies at optimal conditions.
- Main losses sources highlighted (under expansion).
- Recommendations for small-scale power generation systems design.

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ABSTRACT

As part of the Enerco_LT (ENErgy ReCOvery from Low Temperature heat sources) project, hermetic scroll expander is candidate for small-scale ORC prototypes. The aim of this work is (i) to investigate on a test bench the performances of a small-size scroll expander which is a converted compressor and (ii) to develop, based on the experimental results, a semi-empirical steady-state model which can be easily integrated as a sub-model in a larger system simulation model.

The expander was tested by means of a superheated vapour cycle (Brayton) fed with R-245fa and providing defined ranges of supply and exhaust operating conditions. The assessment of the internal unknown variables has permitted the derivation of the model correlations. The supply pressure drop and the internal isentropic efficiency are expressed as polynomial laws of the main working conditions. The model was validated by comparing predictions to the experimental results which has shown a fairly good agreement and accuracy.

The experimental investigation has revealed promising performances of the hermetic scroll expander given at high supply conditions. The net efficiency of the combined expander-generator reaches 70% from supply pressures of 20 bar. Furthermore, the numerical investigation using the developed model has pointed out the performance deterioration when the pressure ratio deviates from the expander built-in volume ratio and indicates consequently how optimizing such machines to ensure the highest performances.

1. Introduction

Waste heat recovery power systems and Organic Rankine Cycles (ORCs) are increasingly getting in vogue as potential future power plants. Several comparative studies [1–10] involve the fluid selection basing on its thermophysical properties in order to improve the system efficiency at various temperature levels of the heat source. Recently, Ayachi et al. [11] have associated the system performance mainly to the architectural recovery design (single-cycle design and cascading-cycle design), to the fluid selection and to the operating condition setting. More recently, the authors [12] have pointed out the existence of an optimal fluid critical temperature, specific to the hot source temperature and the pinch setting; an empirical expression was derived for dry and quasi-isentropic pure fluids and appears to be useful for primary selection of the working fluids. The authors have also shown that the blends have the potential to meet high efficiency and environmental friendly objectives. Besides, the supercritical operating conditions could contribute to the efficiency improvement [11–13].

On the other hand, the system performance strongly correlates with that of its unitary components, especially the expander. The selection of the expander is usually related to the size and the

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Nomenclature

Latin letters

A	area (m^2)
d	pipe internal diameter (m)
D	cylinder external diameter (m)
Gr	Grashof number
h	specific enthalpy (J/kg)
H	cylinder height (m)
L	flange length (m)
$\dot{m}$	overall mass flow rate (g/s)
$\dot{m}_{leak}$	leakage mass flow rate (g/s)
$\dot{m}_{th}$	theoretical mass flow rate (g/s)
N	rotational speed (rpm)
Nu	Nusselt number
P	pressure (Pa) or (bar)
Pr	Prandtl number
$\dot{Q}$	heat flux (W)
Ra	Rayleigh number
Re	Reynolds number
s	specific entropy (J/kg K)
T	temperature (K) or (°C)
U	heat transfer coefficient (W/m^2 K)
V_{sw}	swept volume (m^3)
$\dot{W}$	internal power (W)
$\dot{W}_{el}$	electrical power output (W)
$\dot{W}_{sh}$	shaft power output (W)
v	velocity (m/s)
ρ	density (kg/m^3)

Greek letters

δ	thickness (m)
ΔP	pressure drop (Pa)
η	efficiency
τ	pressure ratio
τ_v	built-in volume ratio
φ	filling factor

Subscripts

a	ambient
c	critical
cp	compressor mode
el	electrical
ex	exhaust
exp	expander mode
ext	external
int	internal
low	lower side
m	mechanical
n	nominal
r	relative
s	isentropic
su	supply
up	upper side
w	shell wall

Acronyms

AD	Average Discrepancy
ORC	Organic Rankine Cycle
SD	Standard Deviation

design of the system. Two main types can be distinguished: kinetic (turbo) and volumetric (positive displacement) types. Similarly to refrigeration applications, displacement type machines are more appropriate to the small-scale power generation units because they are characterized by lower flow rates, higher pressure ratios, much lower rotational speeds and lower costs compared to turbomachines. In particular, the scroll expander well suits the Organic Rankine Cycles and offers valuable features, mainly: the ability to be obtained by the retrofitting of existing scroll compressors commercially available, the few moving parts, the low level of noise and vibration and the high reliability.

Most of the investigations conducted on scroll expanders have targeted the open-drive type. Yanagisawa et al. [14] have provided experimental data regarding an oil-free open-drive air expander and have observed that the performances are significantly lowered by the mechanical losses resulting on one hand from the bearing and the auxiliary crank mechanism and on the other hand from friction between the non-lubricated moving elements. The experimental results have shown a volumetric efficiency of 76% and an isentropic efficiency of 60% achieved under supply pressure of 6.5 bar and rotational speed of 2500 rpm. Manzagol et al. [15] have studied the case of cryogenic scroll expander tested on a frigorific Brayton cycle for a helium liquefaction application. The isentropic efficiency has reached ranging from 50% to 60% under inlet gas conditions of 7 bar and 35 K. Aoun and Clodic [16] have retrofitted an oil-free open-drive scroll machine and have substituted the original gasket by a hand-made polytetrafluoroethylene (PTFE) gasket more adapted for high temperature applications about 190 °C. The experimental results of the vapour expander have shown a maximal volumetric efficiency of 63% and a maximal isentropic efficiency of 48% reached under supply pressure of 3.8 bar and rotational speed of 2000 rpm.

To date, the use of the scroll expander for small-scale power generation systems [17–27] is still under investigation and at an early stage of development. Lemort et al. [17] have tested, by means of an ORC prototype fed with R-123, the performance of an oil-free open-drive scroll expander having kinematically rigid configuration and driving asynchronous machine. The results have shown an expander isentropic efficiency ranging from 42% to 68% under pressure ratios varying from 2.7 to 5.4 and rotational speeds varying from 1771 to 2660 rpm. The authors have pointed out that the internal leakages are responsible for the major part of the performance loss and associated these leakages to a large flank clearance between the moving elements; they have also observed that the leakages increase as well as the rotational speed decreases. Their resulting model was integrated as a sub-model into a numerical ORC model [18]. Recently, Ibarra et al. [22] have used and simplified the scroll model presented by Lemort et al. [17] to carry out a part-load simulation of a 5 kW_e ORC plant. More recently, Chang et al. [24] have investigated the performance an oil-free open-drive scroll expander by means of a low-temperature ORC system fed with R-245fa and operated under variable rotational speed and superheating conditions. The authors have measured a maximum expander efficiency of 73% at a rotational speed of 1535 rpm. They have pointed out that the expander efficiency decreases with the increase of the rotational speed. Another recent study [25] has adopted an open-drive scroll expander to serve as an air-machinery energy converter in a new concept of hybrid power generation system coupling mechanically a kW-level wind turbine and a small-scale Compressed Air Energy Storage (CAES) unit. The simulation and experimental studies have concluded that the proposed hybrid system is feasible and can provide a good smoothing of the wind power fluctuation. Few other power generation studies have investigated the performances of the hermetic-type