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Experimental study of an oil-free steam piston expander for micro-combined heat and power systems

Jean-Louis Bouvier [a], Vincent Lemort [b], Ghislain Michaux [a], Patrick Salagnac [a,*], Thiebaut Kientz [c]

[a] LaSIE (UMR-CNRS 7356), Université de La Rochelle, Av. M. Crépeau, 17042 La Rochelle Cedex 1, France
[b] Thermodynamics Laboratory, Université de Liège, Campus du Sart Tilman, B49, 4000 Liège, Belgium
[c] Exoès, 6 Avenue de la Grande Lande, ZI Bersol, 33170 Gradignan, France

HIGHLIGHTS

- We study experimentally a small size oil-free steam piston expander.
- The electrical power output ranges from 740 to 2400 W.
- An empirical model is developed.
- This model is used in a sensitivity analysis on the expander.

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ABSTRACT

This paper presents an experimental study conducted on an oil-free steam piston expander for micro-combined heat and power systems. This expander can produce electrical power (between 740 and 2400 W) with a significant range of supply temperature (between 260 and 340 °C) and pressure (between 20 and 34 bar). The expander electrical power output exhibits a fast dynamic response to a change of working or supply fluid conditions. The reached expander overall isentropic efficiency (including electrical generator efficiency) was between 19% and 40%.

An empirical model has been developed in order to conduct a sensitivity analysis of the system by varying working variables such as supply and exhaust pressures, rotational speed and supply temperature. The parameters of this model have been identified using experimental results. The sensitivity analysis showed a limited increase of the electrical power output with a rotational speed until 900 rpm and a reduction of the power output for values beyond 900 rpm. It also highlighted the significant positive impact of the supply pressure on the electrical power output and the negative impact of the superheating on the expander overall isentropic efficiency.

The obtained results are useful for the future control of the expander integrated into a Rankine cycle.

Since the fluid at the expander exhaust is steam at a pressure close to 1 bar, it is possible to produce heat at a temperature close to 80 °C, which is sufficient for most domestic applications (heating or direct hot water production).

1. Introduction

Vehicles waste heat recovery, micro-generation and micro-combined heat and power systems (micro-cogeneration) are technologies that can be potential solutions to the energy crisis we are facing today [1,2]. Rankine cycles are widely applied to these small-scale systems. Frequently, the fluid chosen is an organic fluid, in a so-called ORC (Organic Rankine Cycle), or water. In both cases, today, one of the most critical components of the cycle is the expander. Numerous studies investigated the choice of the thermodynamic cycle and of the expander with respect to the temperature and the power of the heat source [3–9]. The present work is focused on the study of a piston expander, which is a promising technology for small-scale systems.

Using organic fluids, some developments of reciprocating expanders appeared in the seventies [10], examples are also cited by Spencer [11]. Few prototypes have been developed nowadays. Baek et al. [12] proposed an experimental investigation on a piston expander in a transcritical CO_2 cycle. Two authors presented a piston expander prototype used for waste heat recovery that can work either with water or ethanol [13,14]. For ORC applications,

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* Corresponding author.
E-mail address: patrick.salagnac@univ-lr.fr (P. Salagnac).

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Nomenclature

h	specific enthalpy (J kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N	rotational speed (rpm)
p	pressure (bar)
r	ratio (–)
T	temperature (°C)
u	standard uncertainty
V	volume (m^3)
$\dot{W}$	power (W)

Greek symbols

ρ	density (kg·m^{-3})
η	efficiency (–)
ϕ	heat flux (W)
ΔT	temperature difference (K)

Subscripts

ev	evaporator
evap	evaporation
ex	exhaust
exp	expander
f	fluid
is	isentropic
p	pressure
sup	superheating
su	supply

Abbreviations

BDC	bottom dead center
EVC	exhaust valve closing
EVO	exhaust valve opening
FF	filling factor
IVC	intake valve closing
IVO	intake valve opening
TDC	top dead center

scroll expanders and turbines are often used [3,15–22]. Some researches on rolling-piston [23], rotary [24,25] and screw expanders [26,27], for small size power plants, are also ongoing.

Two parameters can be used to characterize the expander geometry: the internal built-in volume ratio and the internal built-in pressure ratio. The internal built-in volume ratio is defined as the ratio between chamber volumes at the end and at the beginning of the expansion phase. The internal built-in pressure ratio is the ratio between the expander supply pressure and the pressure at the end of the expansion process (C in Fig. 2). The latter may be lower or higher than the pressure at the exhaust of the expander. It is calculated knowing the supply conditions of the expander and considering an isentropic expansion. The best efficiency of the expander is obtained, neglecting pressure drops at intake and exhaust valves, when the system or external pressure ratio (r_p) is close to the internal built-in pressure ratio [28,29].

Scroll expanders are also suitable using water but have a relatively low internal built-in volume ratio (typically ranging from 1.5 to 3.5). Aoun and Clodic [30] obtained an isentropic efficiency of 48% for an expander with an internal built-in volume ratio of 3.2. Lemort et al. [31], testing a scroll expander with an internal built-in volume ratio of 4.1, reached a maximum isentropic efficiency greater than 55% with pressure ratios up to 15.

Reciprocating expanders are often chosen with water as working fluid because this technology can achieve larger built-in volume ratios (typically ranging from 6 to 14) than scroll or screw expanders [32] and they are able, unlike turbines, to handle liquid droplets [33]. In the seventies, the development of both models and experiments has been done for the sake of car propulsion with steam engines [34,35]. The maximum power of the experiment conducted by Syniuta and Palmer [35] was 104 kW with a supply steam temperature of 540 °C and a pressure of 70 bar. The tests were performed with a 2.2 L four-cylinder lubricated expander. More recently, investigations have been conducted by the Australian National University [36–38] in order to couple a steam expander and dish solar collectors. For powers between 15 and 35 kW, the global efficiency (expander power output divided by the thermal power input) was between 14% and 17% with a steam temperature of 400 °C and a pressure between 15 and 60 bar. The 2.6 L three-cylinder lubricated expander tested had a built-in volume ratio between 10 and 15.8 [36]. Glavatskaya et al. [39] investigated manufacturer's data related to a steam expander with a pressure ratio between 20 and 40 and a temperature between 280 and 320 °C. The reached internal power was between 2 and 7 kW for an isentropic efficiency ranging from 55% to 70%. Leduc and Smague [40,41] tested a four-piston swash plate expander with internal built-in volume ratio of 9.1. Results presented were obtained with a supply pressure of 19.2 bar and a supply temperature of 309 °C for an exhaust pressure of 1.2 bar. The reached isentropic efficiency was about 40% for a power output of 1 kW.

A theoretical study on a steam lubricated reciprocating expander and its control has been performed by Badami and Mura [42] with an internal built-in pressure ratio of 100. A dynamic model including detailed intake and exhaust phases has been developed by Ferrara et al. [43]. A deterministic approach has been chosen by Clemente et al. [28] in order to compare a scroll and a piston expander. It shows that with high external pressure ratios the cycle efficiency can be increased by the use of a reciprocating expander. Semi-empirical models based on a set of experimentally identified parameters are also reported for a piston expander [32,39]. Simplified models, often based on an ideal cycle, are frequently used in optimization studies [44,45].

Lubrication of piston of the expander requires extra components (oil separator, pump, etc.) and lubricants can be unavailable or expensive for some working fluids, such as water, operating at high temperature levels. Thus, using an oil-free expander presents several advantages. By "oil-free piston expander" one usually means a piston expander whose parts in contact with the steam (i.e. piston and valves) are not lubricated. The goal is to prevent oil from being mixed with the steam. In an oil-free piston expander however, mechanical sub-systems which are not in contact with the steam (i.e. crankshaft, bearings, cams, ...), are usually oil-lubricated. Three examples of expander with oil-free piston rings can be reported. Seher et al. [14] tested a 14 kW single-cylinder double acting type expander with a maximum pressure of 32 bar and a maximum temperature of 380 °C. A publication of Buschmann et al. [46] presents an efficiency map of a 50 kW three-cylinder expander for a steam pressure of 50 bars and a temperature of 500 °C. They also performed a 250 s dynamic test with a load variation. The last example is the expander used in the present study that has been described by Daccord et al. [47].

This paper presents detailed experimental results and analysis on an oil-free steam piston expander. The aim of this study is to contribute to the knowledge of small size expanders that can be used for waste heat recovery or micro-combined heat and power systems. Several authors claimed that more experimental research