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Testing and modelling of a novel oil-free co-rotating scroll machine with water injection

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HIGHLIGHTS

- Performance of novel oil-free co-rotating scroll expander presented.
- Water injection allows reaching quasi-isothermal expansion process.
- Comparison between experimental data, semi-empirical and deterministic models.
- Flank leakage, water injection and rotor speed effects have been analyzed experimentally.
- Design guidelines for co-rotating scroll improvement proposed.

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ABSTRACT

Efficient compressed air energy storage requires reversible isothermal compression and expansion devices. The isothermal compression and expansion processes can either be approached by several stages with intercooling or by the more convenient injection of a liquid, often water. While volumetric machines are readily available for dry processes the compression and expansion of a gas with the presence of liquid is still problematic. The concept of a co-rotating scroll has been identified as a promising technology to cope with the presence of liquid. The current paper discusses the first experimental results of an oil-free co-rotating scroll prototype tested in expansion mode on a wide range of rotational speeds, varying water injection flow rates and with different nominal flank clearances. A maximal overall isothermal efficiency of 34% and a maximum output power of 1.74 kW_{el} were measured with this first prototype, providing the proof of the technical feasibility of the oil-free co-rotating scroll expander concept. The experimental data indicate a positive effect of water injection suggesting good heat transfer behaviour between the water and the air in the individual chambers, which is a result of the relatively long residence time compared to other volumetric concepts. The experimental sensitivity analysis yields a strong dependency of the machine performance on both the nominal flank clearance and on the injected water rate. The analysis through a semi-empirical model suggests the inversion of a classical trend, i.e. the increase in total leakage area with rotor speed. This is resulting from the centrifugal loads acting on the flanks and deforming them to produce increased radial and flank clearances. The injection of water is suggested to significantly decrease the leakage. A deterministic reduced order model of the co-rotating scroll expander was developed in order to better understand the governing phenomena within the machine and to provide design guidelines for further prototypes. A novel leakage model takes into account for the structural deformation of the flanks and the scroll involutes as a result from the rotor speed. By means of this comprehensive thermodynamic model, mechanical power, mass flow rate and exhaust temperature were predicted within a range of ±12% and ±4 K respectively compared to experimental data. The calibrated model suggests an achievable isothermal efficiency of 87% for an improved co-rotating scroll concept, thus offering promising perspectives not only for compressed air storage, but also for wet expansion in Absorption Power Cycles, trilateral flash cycle and Organic Rankine Cycles.

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Nomenclature

1,2,3...11	test-rig state points
A	area (m^2)
AM	actual measure
Comp	compressor
D	pitches of the scroll wrap (m)
Exp	expander
FF	filling factor (–)
FEA	finite element analysis
FS	full scale
H	height of the scroll wrap (m)
h	enthalpy (kJ/kg)
k	polytropic index (–)
L	length of the wrap (m)
$\dot{m}$	mass flow rate (kg/s)
MG	motor-generator
N	rotor speed (Hz)
n	number of the chamber
P	pressure (kPa or bar)
Q	heat flow (kW)
R	individual gas constant (kJ/kg K)
r	radius (m)
T	temperature (°C or K)
t	thickness of the scroll (m)
V	volume (m^3)
$\dot{W}$	mechanical power (kW)

Greek symbols

τ	torque (Nm)
Π	pressure ratio (–)
ε	eccentricity (mm or m)
ω	angular frequency (rad/s)
φ	angular error
δ	clearance gap (m or mm)
η	efficiency
θ	angle (rad/s)
γ	adiabatic index (–)
ρ	density (kg/m^3)

Subscripts

ad	adapted
add	added
air	air
c	centrifugal
ch	chamber
def	deformation
disc	discharge
elect	electricity measured
ex	exhaust
f	flank
i	simulation steps
in	inlet
isoch	isochoric
kiss	kissing point
leak	leakage
loss	mechanical losses
m	medium
max	maximum
meas	measured
mech	mechanical
mix	mixture of water and saturated wet air
net	net
nom	nominal
o	initial
over	overall
out	outlet
pred	predicted
pump	pump
r	radial leak
rad	radial
red	reduction
shaft	mechanical power in the shaft
su	supply
suc	suction
teeth	section of the spiral
total	total
v	constant volume
water	water injected

1. Introduction

Small-scale compressed air energy storage (CAES) is a promising technology to store energy during off-peak periods [1]. However, the main drawback of CAES is the low round-trip efficiency due to the irreversibilities produced during the compression and expansion processes [2]. In order to reduce these irreversibilities Lemofouet proposed to inject water during the compression and expansion processes to approach isothermal processes [3]. The injected water is suggested to act as a heat reservoir removing or adding heat during compression or expansion, thus reducing the thermal losses. The main challenge of isothermal CAES systems, however, is the need of a reversible compression and expansion device that is able to cope with significant liquid injection without oil lubrication.

Liquid ring machines [4], water injected twin screws [5] and scrolls [6,7] have been identified as promising technologies for this application. The first one is the most suitable to operate in presence of liquid since its working principle is based on the interaction of a liquid ring with the processed gas. However, the power consumption required to keep the liquid ring in motion is significant, thus the efficiency (less than 50%) is low compared to other concepts [8,9] and the advantage of isothermal processes is lost. Screw compressors have been widely studied and commercialized, they yield competitive isothermal efficiency and reliability [5]. Their drawback, however, is the high manufacturing cost for reduced capacity applications [10], which limits its use to medium or large-scale systems. Scroll technology has been investigated for isothermal processes with water injection by Iglesias and Favrat [7] and for liquid-flooded operation by Hugenroth et al. [11] and by Bell et al. [12]. Compared to other positive displacement machines this technology offers promising features such as the ability to operate in presence of liquid, a competitive cost at low power range (1–10 kW) and a relatively high power density [7].

The scroll technology is categorized into orbiting and co-rotating concepts. The orbiting concept, which is thoroughly understood and widely spread in mechanical vapour compression cycles [13] and in Organic Rankine cycles [14]. It is composed of a fixed and of an orbiting scroll that experiences a translational motion along a circular trajectory imposed through both an eccentric drive and a kinematic guidance system. This mechanical guidance system can be achieved either through a rigid orbit control such as idler pins [15] or through an anti-rotation mechanism such as Oldham coupling [16] or interdigitated teeth [17]. Kinematically