2014

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Mendoza Toledo, Luis; Iglesias, Angel; Favrat, Daniel; and Schiffmann, Jürg, "Experimental Investigation of Water Injection in an Oil-Free Co-rotating Scroll Machinery for Compressed Air Energy Storage" (2014). *International Compressor Engineering Conference.* Paper 2324.
https://docs.lib.purdue.edu/icec/2324

Experimental Investigation of Water Injection in an Oil-Free Co-rotating Scroll Machinery for Compressed Air Energy Storage

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ABSTRACT

The high efficient isothermal reversible machine creates the opportunity to be used as a very efficient small-scale compressed air energy storage (CAES). This new type of CAES links the large-scale smart grid to the decentralized electricity production from renewable sources. In this article is presented an experimental study about a novel oil-free co-rotating scroll machine currently in a prototyping stage. This co-rotating scroll unit does not have a discharge check valve that gives it the possibility to operate as compressor and also in expander mode without any hardware modifications. The distinctive feature of this machine in comparison with an orbiting scroll machine is two mobile involutes working in synchronized co-rotation, one relative to another. The prototype was tested in two experimental test rigs (compressor and expander test rig mode) to determine the viability of the working principle, preliminary performance and also the effect of the water injection on the mechanical power and efficiencies. The experimental results demonstrate that the principle of co-rotating could operate without damage up to a rotational speed of 83.3 Hz in compressor mode (without lubrication). The maximum overall isentropic efficiency obtained from the experimentation in compressor and expander modes were 39 % and 32 %, respectively. The maximum compressor's volumetric efficiency and expander's filling factor were 45 % and 2, respectively. The water injection has a positive effect on the performance because it improves the polytropic coefficient and this in turn decreases/increases the power consumption/production of the unit.

Keywords:
Compressed air energy storage, Co-rotating scroll machinery, Isothermal compression and expansion, Oil-free, Water injection inside compressor and expander.

1. INTRODUCTION

A typical electrical load profile varies throughout the daily, monthly, seasonal and yearly cycles while the electricity generation tends to be different from the electrical load profile (Feuerriegel and Neumann, 2014). This difference produces the called "peaks demand fluctuation". For this reason, several authors have proposed various energy storage systems to accumulate energy during the off-peaks periods and release the energy during the load peaks (Díaz-González et al., 2012).

Compressed air energy storage (CAES) is a good way to store energy in the form of compressed air in a deep underground geological vessel or reservoir. However, the main drawbacks of CAES are the geological structure reliance and the large scale of such systems, which substantially limit their usability. A highly efficient isothermal reversible machine (Lemofouet-Gatsi, 2006) creates the opportunity to be used as a very efficient small-scale compressed air energy storage (CAES). The compression/expansion of an air-water mix (water chosen instead of oil because of oil incompatibility with air humidity) allows to approach an isothermal process without the inherent challenges of high temperature or high thermal losses. However, in order to implement these systems, substantial technological challenges related to the compressor/expander unit have to be solved. The compressor/expander devices are key components for efficient CAES.

Two types of compressor/expander units are found in literature (Martin, 2004): dynamic and volumetric. The first ones are primarily used for large-scale systems with low pressure ratios. The second ones are suggested to work with high compression/expansion ratios yielding good performance at low capacity. In this work, it is proposed to use a scroll compression/expansion system due to its high compression/expansion ratio, low rotational speed and potential to accept water injection for isothermal operation. However, it is required that the system operates without oil-based lubrication since the isothermal compression and expansion process will be achieved by water injection. It turned out to be difficult to find a suitable oil-free scroll compressor/expander in literature and on the market. This paper therefore refers to a novel co-rotating scroll unit that can be operated successively in the compressor mode followed by the expander mode. Preliminary results in turbine mode were presented in (Iglesias and Favrat, 2013) and this paper shows the first results in both modes (compressor and expander).

2. CO-ROTATING SCROLL MACHINERY

There are two different categories of scroll machines: orbiting and co-rotating. The first one is composed of a fixed and of an orbiting spiral. The second category uses two scrolls rotating together around their own center at the same rotational speed and direction. The co-rotating scroll concept was initially proposed by (Morishita et al., 1988) for a vacuum pump application and their conclusion was that the co-rotating vacuum pump unit had better performance than an orbiting scroll unit. The main reasons of this improvement are: easily decrement of the internal clearances and less rubbing speed between the scrolls (one seventh less in co-rotating scroll).

2.1 Co-rotating working principle

Figure 1 shows the operating principle of the co-rotating scroll machinery in compressor/expander mode. Both scrolls rotate around their own axis and both axis are separated by a determined distance r = {(p/4)-t} to avoid radial leakage and mechanical locking (Morishita and Sekiya, 1994). In this machinery, the compression/expansion process inside of the co-rotating scroll machinery is performed slowly producing less thermal irreversibilities and also the compression/expansion process is made simultaneously in two symmetrical chambers, therefore its behavior results in a smooth operation, less vibrations, noiseless, little fluctuations of the torque and exhaust pressure.

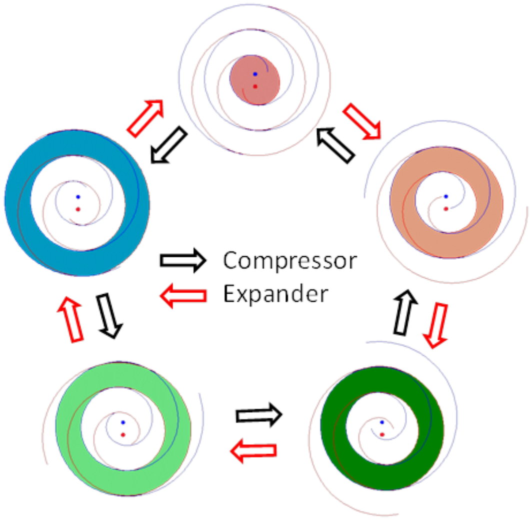

Figure 1: Operating principle of a co-rotating scroll machine in compressor and expander mode.

Other features of the co-rotating scroll type in comparison with the orbiting scroll type are the positions and directions of the radial clearances between both scrolls. In the orbiting technology the positions of the radial clearances changes around the fixed scroll (Figure 2a) in a straight line, rotating. While, in the co-rotating technology the positions of the radial clearance are formed into a line, thus the directions of the clearances always are the same (Figure 2b). Therefore, the radial clearances of the co-rotating scroll type can easily be sealed by adjusting the external force added to the driven scroll in the radial direction.

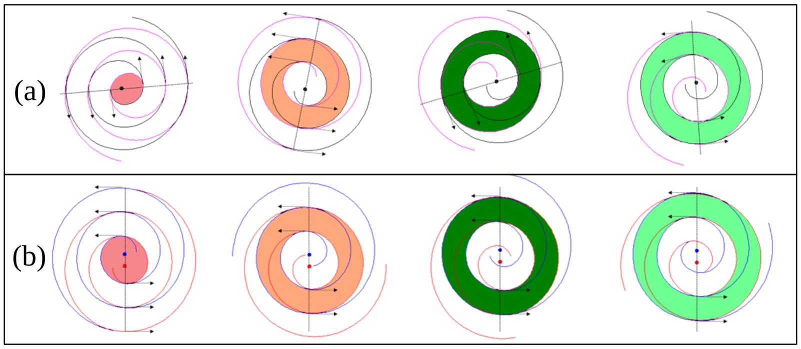

Figure 2: Radial leaks directions for (a) Co-rotating scroll and (b) Orbiting Scroll.

Small deviations between the centers or the alignment of the scrolls considerably affect the size and positions of the clearances (Figure 3).

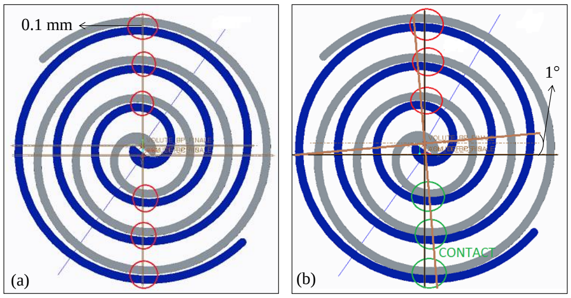

Figure 3: Effect of the (a) center and (b) alignment deviations on the contact points and clearance size.

From the geometrical study of the co-rotating scroll is found that in order to obtain good performance, the deviations between the scrolls center and alignment should be lower than 0.1 mm and 1°, respectively.

2.2 Design of the co-rotating scroll machinery

At the laboratory for applied mechanical design of the EPFL, a co-rotating scroll prototype that can be operated as a compressor/expander unit (Molyneaux et al., 1997) has been proposed. The main characteristics of this unit are a suction volume in compressor mode of 97 cm^3/rev and a volumetric ratio close to 3.

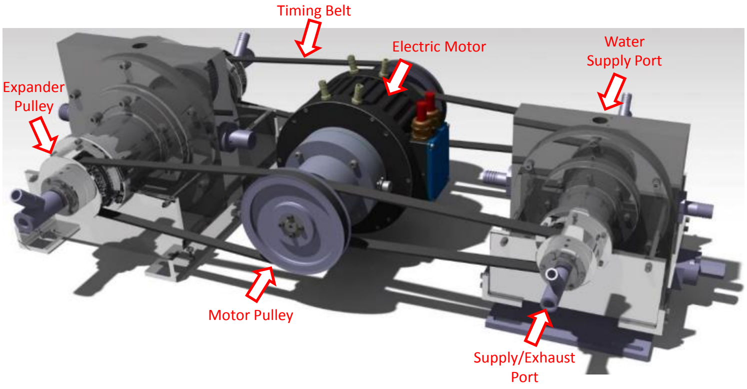

Figure 4: Schematic representation of the compressor/expander unit.

To ensure the perfect synchronization of both scrolls, a configuration with two timing belts coupled to one electric motor was proposed (Figure 4). This configuration allows for both scrolls to turn at the same rotational speed and also for adjusting their angular and radial alignment.

Another particular characteristic of this co-rotating scroll unit is the shape of the scroll paths. Indeed this unit has a particular behavior when the pressure ratio between the discharge and suction port decreases (Chen et al., 2002). The flank gaps increase in some areas and decrease in other areas because the angular contact bearings allow the scroll to tilt. This phenomenon is caused by an overturning moment as shown in Figure 5.

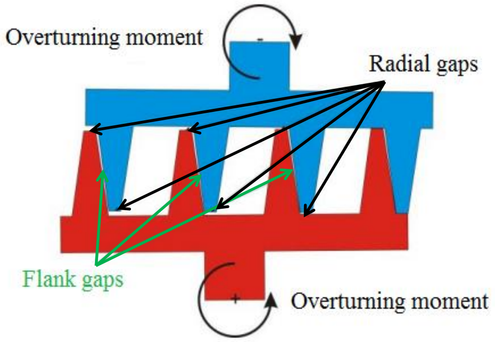

Figure 5: Flank and radial gaps due to an overturning moment.

3. EXPERIMENTAL METHODOLOGY

The co-rotating prototype was tested with the aim to shown its technical feasibility. In a first step the mechanical integrity of the system was tested with the objective to investigate whether the co-rotating system could operate safely using timing belts. In a second step, the preliminary performance of the machine was investigated first in compressor and then in expander mode.

3.1 Experimental setup in compressor mode

Figure 6 shows an open-loop air test bench used to test the co-rotating scroll compressor. It can be seen that there are two separate networks. One of these (yellow line) networks represents the stream of air that is compressed and the other one (blue line) is the water that is sprayed into the compressor to achieve isothermal operation.

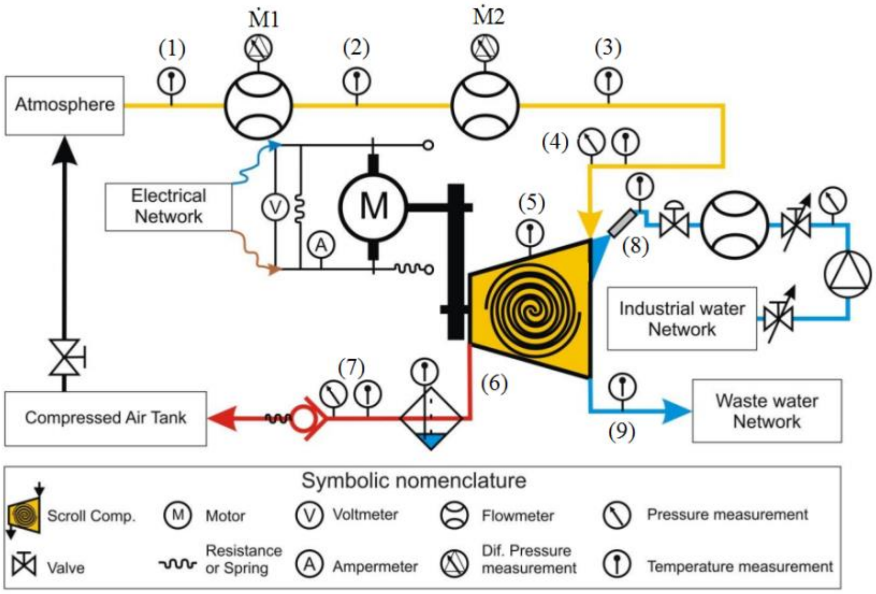

Figure 6: Open-loop air test bench in compressor mode.

The stream of air from the ambient (1) is compressed (5) by the co-rotating scroll machine. Prior to compression, however, the air (4) is mixed with a controlled quantity of finely pulverized stream of water (8) at the inlet ports of the compressor the stream of water and air is compressed (6), dehumidified (7), and finally accumulated in a reservoir. The power required to compress the air is provided from an electrical motor through two timing belts driving each of the two shafts.

The mass flow rate of air that enters the compressor is measured by means of two different types of flow meters connected in series: a laminar flow meter ($\dot{M}1$) and an orifice plate flow meter ($\dot{M}2$). Three thermocouples (1-3) are positioned at the inlet, at the intermediate position and at the exit of the group of flow meters to determine the density when calculating the flow in each flow meter. Pressures and temperatures are measured at the supply and exhaust ports of the compressor (4 & 6). Prior to injection and after separation the water temperature is equally measured (8 & 9). The overall electrical power consumption is measured by means of the input current and voltage. During the tests, the measurements were recorded by a data acquisition system that also presented the trends of the variables on-line.

3.2 Experimental setup in expander mode

Figure 7 shows the open-loop air test bench used to test the co-rotating scroll machine in expander mode. The system configuration is nearly the same as for the compressor mode rig, with the exception that the inlet becomes the exhaust. An air stream is taken from a conditioned compress air network (1), then it mixed (2) with the pulverized water (8), the air is expanded (3) and the water removed from the air (5). In expander mode the electric machine is switched in generator mode.

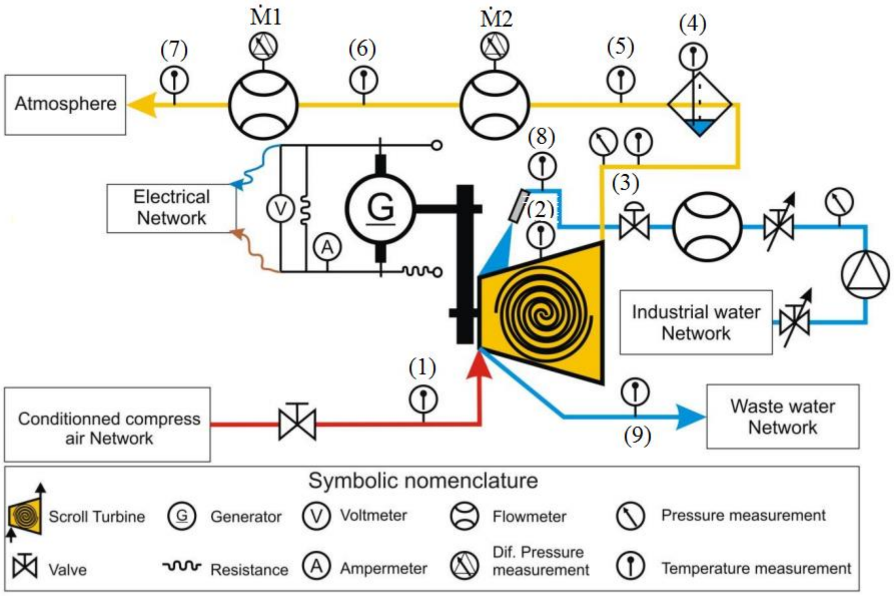

Figure 7: Open-loop air test bench in expander mode.

The measured power produced by the expander was obtained from the input current and voltage produced by the motor operated in generator mode. Also, during the tests, the measurements were recorded by a data acquisition system that also presented the trends of the variables on-line.

3.3 Performance indicators

In this section the performance indicators of the unit working in compressor and expander mode are presented. The total amount of electrical power consumption/production were calculated by means the voltage (V) and current (A), as listed in equation (1).

$$\dot{W}_{el} = V \cdot A \tag{1}$$

Since water is injected to approach an isothermal process, the isentropic efficiency is not the appropriate way to measure the machine performance. In literature, the efficiencies of the compression and expansion machines are compared to isentropic transformations. I this paper it is proposed to use "the overall isentropic efficiency concept". The overall isentropic efficiency has accounted all the irreversibilities of the unit like: electrical and power losses, internal leakages and compression/expansion losses. The definition of the overall isentropic efficiency (Zanelli and Favrat, 1994) is related to the operation mode (compressor or expander). The first one (Equation 2) is defined as the ratio between the power consumption through an adiabatic and reversible compression process and the total electrical consumption. The second one (Equation 3) is defined as the ratio between the electrical power production by an adiabatic and reversible expansion process:

$$\eta_{iso,overall,comp} = \frac{\dot{m}_{su} \cdot (h_{su} - hs_{ex})}{\dot{W}_{el}} \tag{2}$$

$$\eta_{iso,overall,exp} = \frac{\dot{W}_{el}}{\dot{m}_{su} \cdot (h_{su} - hs_{ex})} \tag{3}$$

The total mass flow rate of air that enters the unit is dependent the operation mode, geometrical volume of the supply chamber, density of the working fluid and also the internal leakages. The performance indicators are the volumetric efficiency (in compressor mode) or filling factor (in expander mode) and are giving in the equations (4) and (5). The volumetric efficiency of the scroll compressor is the ratio between the theoretical mass flow rate (Equation 5) that fills the supply chamber in compressor mode and the total mass flow rate that enters to the compressor, it can be calculated by means of the Equation (5).

$$\dot{m}_{th,comp} = VS_{ch,su} \cdot N_{comp} \cdot \rho_{su} \tag{4}$$

$$\eta_v = \frac{\dot{m}_{su}}{\dot{m}_{th,comp}} \tag{5}$$

The filling factor of the scroll expander is the relationship between the theoretical mass flow rate that should fill the supply chamber to the total mass flow rate (measured) that actually enters to the expander (Zanelli and Favrat, 1994).

$$FF = \frac{\dot{m}_{su}}{\dot{m}_{th,exp}} \tag{6}$$

$$\dot{m}_{th,exp} = VS_{ch,ex} \cdot N_{exp} \cdot \rho_{su} \tag{7}$$

Since the preliminary tests were made in unsteady-state conditions, it is not possible to calculate the uncertainty of the results; moreover in the test rig the mechanical power was not measured, therefore the mechanical efficiency and the mechanical power consumption/production of the unit are not determined.

4. TESTS RESULTS

4.1 Tests in compressor mode

In this section the experimental results obtained from the experimental tests in compressor mode with and without water injection are presented.

4.1.1 Tests without water injection: Figure 8 shows the experimental results of the compressor without water injection. The performance indicators determined from these tests are (a) exhaust pressure, (b) electrical consumption, (c) volumetric efficiency and (d) overall isentropic efficiency at different rotor speeds, carried out at constant inlet conditions (101.3 kPa, 293 K). Since the tests were performed in unsteady-state conditions they are represented as a function of time.

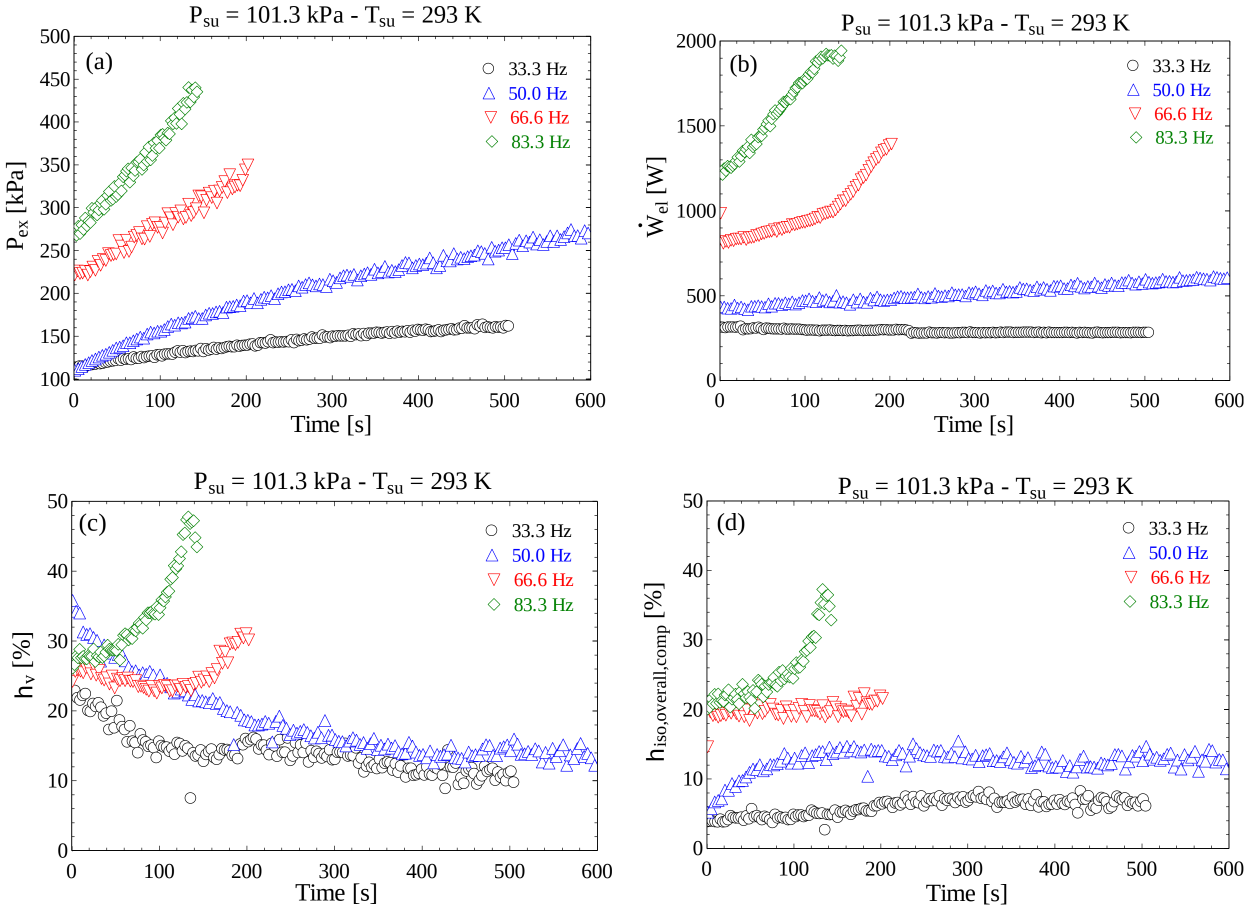

Figure 8: Effect of the rotational speed on the (a) exhaust pressure, (b) electrical consumption, (c) volumetric efficiency and (d) overall isentropic efficiency.

Figure 8a shows the exhaust pressure achieved at different rotor speeds (from 150 kPa at 33.3 Hz to 450 kPa at 83.3 Hz). It is possible to obtain higher exhaust pressures, however, they could not be reached due to the elevated exhaust temperatures (no water injection).

In compressor mode, the maximum power (Figure 8b) obtained from the experimentation was about 2 kW (to compress air from 101.3 kPa to 450 kPa at 83.3 Hz). Theoretically, the volumetric efficiency should decrease with increased supply pressures, however in these tests (Figure 8c) the volumetric efficiency has a disparate behaviour. At lower rotational speeds (33.3 Hz and 50 Hz) the volumetric efficiencies decreases from 36% to 12% but for higher rotational speed (66.6 Hz and 83.3 Hz), the volumetric efficiency increases from 25% to 49%. Finally, it can also be seen (Figure 8d) that the overall isentropic efficiencies increases with the rotational speeds and the maximum overall isentropic efficiency obtained was about 39%.

4.1.2 Tests with water injection: Figure 9 shows the experimental results obtained from the scroll compressor's tests with water injection. The performance indicators determined from these tests are (a) power consumption and (b) mass flow rate. The tests were carried out with a constant rotational speed of 33.3 Hz, supply pressure of 101.3 kPa, supply temperature of 293 K using different mass flow rates of water injection (without water injection, 0.1 l/min and 0.2 l/min).

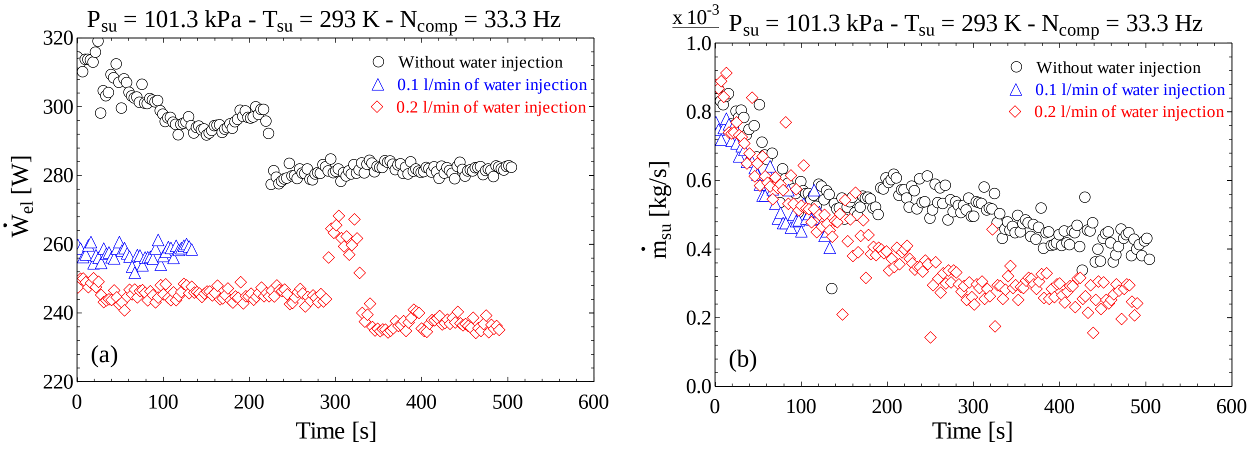

Figure 9: Effect of the water injection on the (a) electrical consumption and (b) mass flow rate.

The experimental tests show that the electrical consumption decreases with the water injection (from 320 W to 235 W). The reason of this decrease is related to the polytropic coefficient drop (more close to an isothermal process). Also it can be seen that the mass flow rates are not affected at the beginning of the test, however at the middle of the test some instabilities were observed.

4.1 Tests in expander mode

In this section are shown the experimental results of the unit in expander mode without and with water injection (Figure 10). The tests were made at several rotational speeds and supply pressures. The tests were carried out at constant supply temperature (293 K) and exhaust pressure (101.3 kPa).

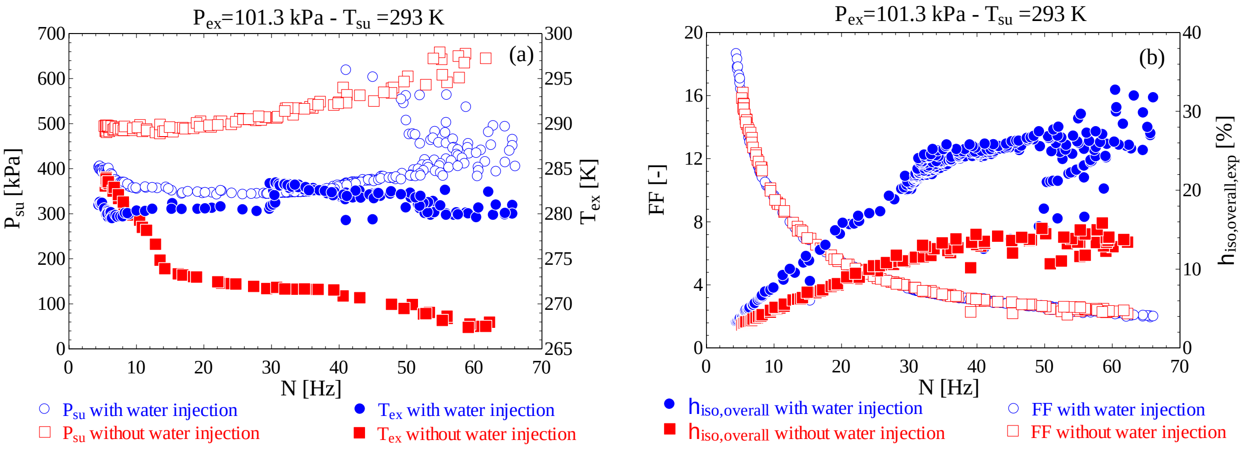

Figure 10: Effect of the water injection on the (a) exhaust temperature, (b) filling factor and overall isentropic efficiency.

Figure 10 shows the effect of the water injection on the exhaust temperature, filling factor and overall isentropic efficiencies in expander mode. It can be seen (Figure 10a) that in the tests without water injection, the exhaust temperature of the expander is lower than the tests with water injection. The reason of this difference is because of the improvement of the polytropic coefficient (the expander works as a quasi-isothermal machine) and therefore an improvement of the overall isentropic efficiency (Figure 10b). However the effect of the water injection hardly improves the filling factor (Figure 10b).

5. CONCLUSION AND FUTURE WORKS

A novel co-rotating scroll unit has been designed, built and tested to work both as compressor or expander for air energy storage applications. The performance of the unit working as compressor and expander have been measured by means of two experimental test rigs and tested with and without water injection.

The working principle of the co-rotating unit driven by two timing belts has been tested. The investigation confirmed that the unit can be operated as compressor and expander without any damage up to 5’000 rpm (83.3 Hz).

Isentropic efficiencies of 39% and 32% were measured for compressor and expander mode respectively. The maximum compressor’s volumetric efficiency and expander’s filling factor were 45% and 2%, respectively. Further improvements can be obtained with higher rotational speeds, pressure levels and increased water injection rates.

The results confirm that water injection has a positive effect on performance since it improves the polytropic coefficient, which decrease/increase the power consumption/production of the machinery.

According to the promising results derived from this investigation, it is necessary to further characterize this unit by means of a comprehensive series of tests to determine the influence of its operational conditions on the unit’s performance.

NOMENCLATURE

$\dot{m}$	mass flow rate	(kg/s)
$\dot{W}$	power	(W)
A	current	(A)
FF	filling factor	(-)
h	enthalpy	(kJ/kg)
hs	enthalpy isentropic	(kJ/kg)
N	rotational speed	(Hz)
p	pitch	(m)
P	pressure	(kPa)
r	difference of the axes	(m)
t	thickness	(m)
T	temperature	(K)
V	voltage	(V)
VS	suction volume	(m^3/rev)

Subscripts

ch	chamber
comp	compressor
el	electrical
ex	exhaust
exp	expander
iso	isentropic
overall	overall
su	supply
th	theoretical
v	volumetric

Greek symbols

ρ	density	(kg/m^3)
η	efficiency	(%)

ACKNOWLEDGMENT

The authors acknowledge the financial support of the Canton Vaud "100 millions pour les énergies renouvelables et l'efficacité énergétique".

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