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Experimental Investigation on a Sliding-Vane Expander for Steam Applications

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Abstract. There are many industrial plants that use steam as an energy vector at different pressure levels, in which pressure reduction is commonly performed by a throttling valve, resulting a totally irreversible process. It is possible to recover this energy through an expander that generates mechanical or electric energy. This work is focused on the analysis of a highly innovative steam expander based on sliding-vane technology. The design principles of the sliding-vane expander and two experimental campaigns are presented. The first experimental campaign allows to assess the reliability of the system with steam as working fluid, the second campaign leads to assess the stability during long-run and the performance of the system. A maximum expander mechanical power of 28 kW is measured. The pressure-Volume diagram of the expansion process is also measured and presented.

1. Introduction

Steam is adopted widely in the industrial sector as an energy vector for direct and indirect thermal uses. Typically, steam is generated in fired boilers at relatively high pressure, transported across the industrial plant and, ultimately, throttled in valves to the desired pressure close to the point of use. Despite this approach is very effective from the control and the investment perspectives, pressure reduction by throttling is an irreversible process that, from a thermodynamic perspective, destroys exergy [1]. Rian and Ertesvåg demonstrate through the analysis of a case study that the destruction of steam exergy by throttling can be avoided largely by the substitution of throttling valves with steam expanders to generate mechanical or electric energy [2]. Additionally, Frate et al. prove that the use of expanders for the pressure reduction of steam can be technically and economically viable under many circumstance [3]. In their turn, Tian et al. analyze numerically the adoption of a twin-screw steam expander as pressure reduction means under fluctuating operating conditions, determining that volumetric and isentropic efficiencies are significant in all the analyzed conditions [4].

This work investigates experimentally the performances of a sliding-vane steam expander under diverse working conditions. Sliding-vane expander, thanks to their low speed, good off-design performance, high expansion ratio, low cost and simple manufacturing, are a viable option for the energy recovery systems. A first prototype of sliding-vane steam expander, able to work with saturated steam, has been realized and tested. The authors investigated deeply sliding-vane expander technology in ORC based energy recovery systems in previous works [5, 6], studying in great detail different working fluids [7] and validating an automated control system [8].

The following sections describe the experimental campaigns organized and executed in this work, present the experimental results discussing them, and finally draws the conclusions.

2. Experimental campaign

The experimental campaign has the purpose to perform a reliability and performance determination on the adopted sliding-vane expander, using saturated steam from an industrial boiler, as the working fluid. The test rig and the test procedure are described in the sections below.

2.1. *Test rig*

The layout of the test rig employed in this work is divided in three main areas. The first area is dedicated to the steam generation, where the low-pressure steam generator is located, with all the equipment needed to produce saturated steam at variable pressure. The second area, separated from the first one through a wall, is the expander room, where the expander with its ancillaries and all the devices aimed to control and to measure the operating conditions are installed. The third area, separated from the previous ones through walls, is the control room, where the operator can monitor the first and the second room in safe conditions, without entering in contact with steam lines. The first two areas are pictured in Figure 1.

Figure 1. Steam generator area (left) and expander area (right) of the test rig employed in this work.

2.1.1. Steam generator

The steam is generated through a diathermic oil boiler, the main technical specification of which reported in Table 1. Gas burner, fed by natural gas, provides the thermal power required to heat up the diathermic oil. The burner is embedded into the thermal oil heater which conveys and leads the hot gases through oil filled bundle tubes. The hot oil, produced by the thermal oil heater, is conducted into the steam generator and it transfers heat to feed water. The diathermic oil is driven by two centrifugal pumps. The oil line directly communicates with a closed expansion vessel pressurized with nitrogen. Nitrogen tank feeds the expansion vessel partially filled with diathermic oil. Two vertical pumps, the evaporator and the expander realize an open Rankine cycle using feed water as working fluid.

Table 1. Steam generator technical specifications

Description	**Value**
Manufacturer	ICI CALDAIE
Thermal Power	465 kW
Rated Pressure	12 bara
Steam flow	680 kg/h

2.1.2. Expander room

The expander room is characterized by two main lines, as illustrated by the process flow diagram in Figure 2. The steam line (in blue) and the oil line (yellow). The first one represents the working fluid flow from the boiler, as saturated steam, to the expander, that can be also vented directly to the ambient when the conditions are not compatible with the expansion process, for example during the boiler startup. The flow regulation is managed acting electrically on two pneumatic valves. Then, after the expansion process, the steam is discharged into the ambient. The oil line provides lube oil to the expander in order to reduce the friction between moving parts during the expansion process. The oil flow rate is managed by a gear pump coupled with an electric motor controlled through an inverter. The oil used for this application is a blend compatible with sliding-vane machines and the temperatures of the steam expansion process.

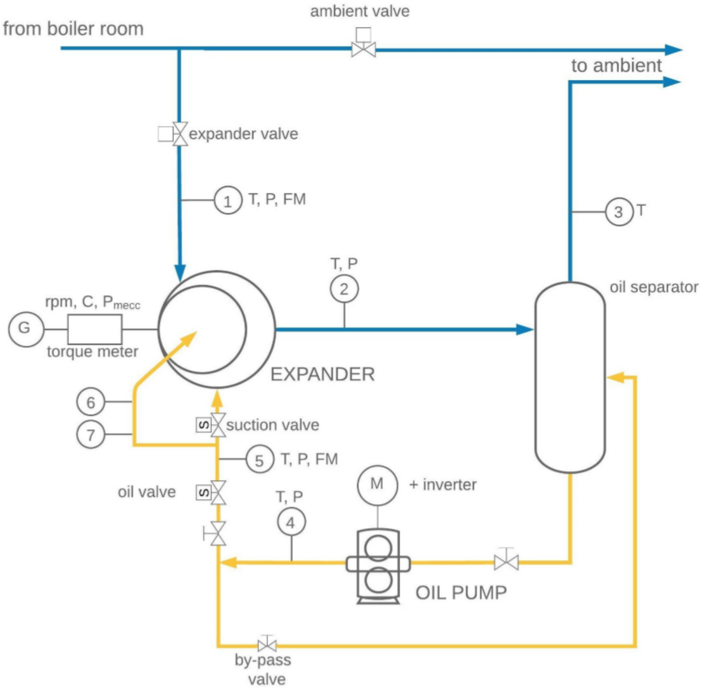

Figure 2. Process flow diagram of the expander area, with the steam (blue) and the oil (yellow) lines.

2.1.3. Sliding-vane expander

The component that realizes the steam expansion process is a sliding-vane expander. This is a positive displacement rotary machine composed by an external cylindrical housing, referred as stator, and an internal circular rotor, smaller than the stator. In the expander, the rotor is eccentrically offset to be tangent to the stator along a tangency line (or arc). The contact line between rotor and stator represents the only sealing between the suction and pressure side of the machine. Radial or tilted slots are obtained in the rotor and will host the vane, which are free to slide along the slot direction itself. During the rotation, under the effect of centrifugal force, vanes slide outwards their slots until their tip gets in contact with the internal stator surface. Hence, each couple of adjacent vanes, thanks to rotor eccentricity, generates a volume, refereed as cell, which is gradually reduced (compressors) or increased (expanders), thus determining a variation of the fluid pressure. The intake and exhaust ports are designed for a proper feeding and evacuation of the working fluid. In the expander a small amount of lubricant is injected, to guarantee lubrication and sealing during the expansion process. The lubricant is also used for the bushings lubrications, that sustain the rotor during the expander rotation. The expander schematic and main geometrical characteristics are reported in Figure 3. The expander is directly coupled with a generator, that converts the shaft mechanical power into electric power.

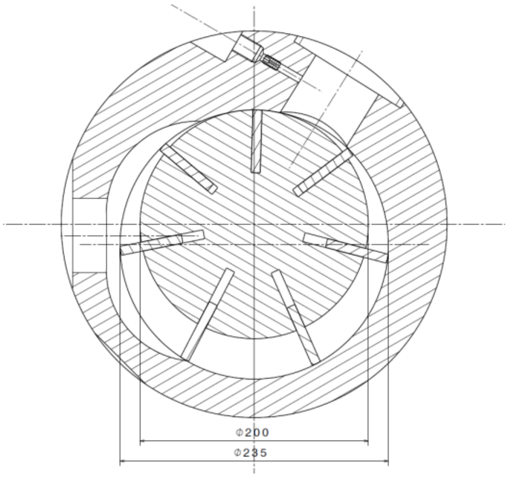

Figure 3. Schematic of the **s**liding-vane expander main dimensions in millimeters.

2.1.4. Instrumentation

The diagram in Figure 1 shows where the instruments reported in Table 2 are placed. The number reported to indicate the position is used also to report the results in the following section. Regarding the diagram, the letter T, P and FM means respectively the instrumentations used: thermocouple, pressure transducer and flow meter, while the progressive number indicates different position on the system, in particular:

1- steam T and P, expander inlet;
2- steam T and P, expander outlet;
3- steam T, separator outlet;
4- oil T and P, pump outlet;
5- oil T, P and FM, injection line;
6- bushing T, motor side
7- bushing T, side opposite to the motor

Four piezoelectric pressure transducers are placed along the end cover of the expander, allowing to investigate deeply the expansion process by reconstructing the indicated cycle.

Table 2. Instrumentation list

Instrument	Model	Unit	Uncertainty
Relative pressure transducer	Remag PR100	barg	0.04
Thermocouple	Tersid T type	°C	0.5
Piezoelectric pressure transducer	Kistler	-	-
Steam flow meter	Ital control Meters M23	kg/h	2% on read value
Oil flow meter	Omega FLR6115D	l/min	0.289
Torque meter	Kistler 4504B1K1N1	N m	0.1
RPM meter	Kistler 4504B1K1N1	rpm	12

2.2. *Test procedure*

For the experimental campaigns, a standard procedure has been identified and followed for both the data collection and the start-up as well as shut-down of the system, as described next.

2.2.1. Start-up procedure

Regarding the start-up procedure, the following is executed.

1. Instrumentation checking.
2. Setting the oil circuit. The valve that opens the oil to the expander is closed, so that the oil circulates only through the pump and the separator, increasing its pressure. The pump is turned on and the by-

pass valve is regulated to match the desired oil injection pressure, considering further pressure drops when the injection valve is open.

3. Start-up of the boiler. As the manufacturer suggests, the boiler is turned-on with the steam valve completely closed, otherwise all the flow will be discharged to the ambient.
4. Valve checking. For safety reasons and for the next steps, the valves inside the expander room are set to discharge all the steam flow to the ambient. This means that the expander valve must be close in position while the ambient valve must be in open. In this phase there is still no steam flow in the expander room.
5. Steam valve opening. Once the steam boiler has reached the design pressure, the steam valve is partially opened. For the previous step, the pressurized steam is discharged into the ambient. At this point, the system is ready to direct the steam flow to the expander.
6. Expander valve opening. Once the operator is ready to run the steam expander, the expander valve is opened and the steam flow starts to go into the expander.
7. Oil valve opening. As soon as the expander valve is opened, the oil valve is opened to lubricate the machine. In this conditions, the incoming steam flow is not enough to overcome all the mechanical resistances and produce positive power. In fact, most of the steam flow rate goes to the ambient branch due to the lower resistance to the flow.
8. Ambient valve closing. Since the flow rate is not enough for the expander, the ambient valve is turned to close position, directing the whole steam flow into the expander.
9. Connection to the grid. With the previous step, the expander starts to rotate and is able to rotate faster and faster. In this condition the expander is connected to the electric grid starting to produce electric power. After the start-up procedure, the steam expander reaches stable condition in terms of temperature and pressure. Nevertheless, during the test, it could be required to regulate the pump rotational speed to respect the constraint on the bushings temperature.

2.2.2. *Shut-down procedure*

Regarding the shut-down procedure, the following is executed.

1. Ambient valve opening. Operating this valve, a fraction of the steam flow goes into the ambient.
2. Expander valve closing. To shut-down the expander, the whole steam flow must be directed to the ambient. Hence, there is no more steam flow incoming into the expander.
3. Disconnection from the grid. Since there is no more steam flow to the expander, no more power will generated, hence, it is disconnected from the grid to avoid power consumption.
4. Oil valve closing. When the expander is shut down, lubrication is no more needed. Moreover, a heavy and unnecessary lubrication of the expander creates problems to the machine.

3. Results and discussion

This section presents the results of the tests conducted following the procedures described above. The aim of test is to measure the system performance and stability. Two experimental campaigns are performed, as described in the next two sections.

3.1. *First experimental campaign*

During the first experimental campaign, a first running of the system is performed, in order to collect the data and characterize the system zero condition. Temperatures in the main points during the start-up are presented in Figure 4 as a function of time, while all temperatures and pressures in all points at steady state in Table 3; other measured values at steady state are presented in Table 4. After the first start-up of the system, the temperature stabilizes and the conditions across the expander are almost constant. During this steady phase, a mechanical power of about 17.4 kW is measured at the expander shaft, and converted to electric power through the electric motor.

The temperature increases during the expander start-up but stabilizes after the first 200s. During the start-up phase the lubrication system must be adjusted in order to control lubrication and sealing and, consequently temperature, during the expansion process.

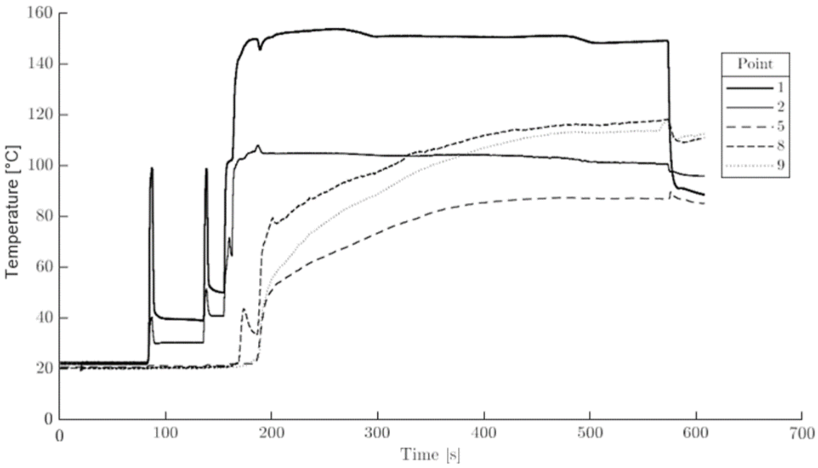

Figure 4. Temperature diagram during first experimental campaign as a function of time.

Table 3. First experimental campaign temperature and pressure at steady state.

Point	Temperature [°C]	Pressure [barg]
1	150.9	4.41
2	103.5	0.23
3	88.2	-
4	99.9	5.5
5	86.9	5.32
6	115.4	-
7	111.9	-

Table 4. First experimental campaign additional measurements at steady state.

Data	Value	Unit
Mechanical power	17.4	kW
Torque	109.9	Nm
Rotational speed	1513	RPM
Steam flow rate	547	kg/h
Oil flow rate	4.02	l/min

3.2. *Second experimental campaign*

During the second experimental campaign, some adjustments to the system have been implemented: thermal insulation was improved to avoid condensation, leading to higher temperature and pressures of the steam flow during the test. Furthermore, a fine tuning of the lubricant injection pressure has been performed, leading to a better lubrication condition of the expander. The improvements can be quantified by comparing data in Table 5 vs Table 3.

As previously, Table 5 and Table 6 show, respectively, the temperature as well as pressure of all points and the additional measurements, all at steady states.

All the mentioned improvements allowed for a better performance, reaching a higher mechanical power produced by the expander thanks to the steam expansion process, as presented in Figure 5 that show its measure during the startup as a function of time.

Table 5. Second experimental campaign temperature and pressure at steady state.

Point	Temperature [°C]	Pressure [barg]
1	156.4	6.14
2	113.6	1.11
3	98	-
4	101.5	15.46
5	88.3	15.03
6	134.4	-
7	122.4	-

Table 6. Second experimental campaign additional measurements at steady state.

Data	Value	Unit
Mechanical power	28	kW
Torque	175.8	Nm
Rotational speed	1521	RPM
Steam flow rate	1034.1	kg/h
Oil flow rate	12.87	l/min

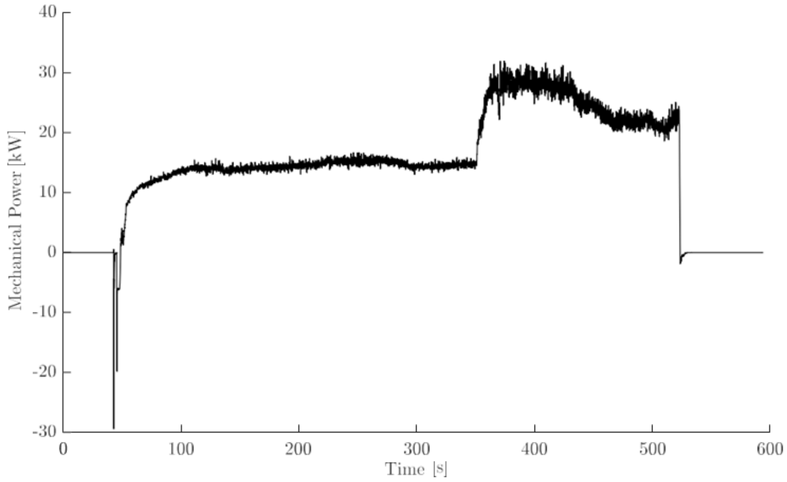

Figure 5. Mechanical power diagram during the second experimental campaign as a function of time.

Figure 6 illustrates the pressure evolution inside the expander as measured by the four piezoelectric sensors that are able to collect pressure during the entire expansion process as well as part of the suction and discharge. By means of the volume evolution inside the expanders, determined from the geometrical features of the machines, it is possible to calculate the expansion indicated power as the area enclosed by the pressure-volume curve and, consequently, the mechanical efficiency of the expander. In this testing conditions, a mechanical efficiency of 85% is reached.

Additionally, Figure 6 shows that an under-expansion happens inside the machine: in the last part of the process, the expander outlet pressure is higher than the atmospheric pressure. This pressure gap is due to the steam-lubricant separator and the steam delivery line.

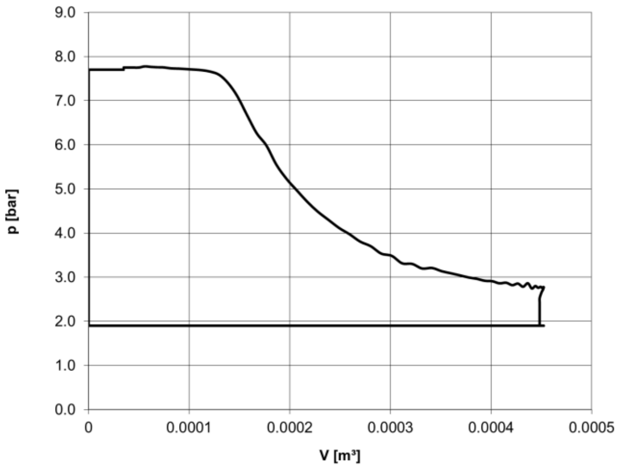

Figure 6. Measured pressure-Volume diagram of the expansion process

4. Conclusions and future works

An experimental study is carried out on sliding-vane expander using steam as working fluid. A defined test procedure has been implemented in order to operate the system in safe conditions. This work draws conclusions as follows.

- During the first experimental campaign, a first running of the system is performed, in order to collect the data and characterize the system zero condition. The system is able to correctly work and recover energy by the steam expansion through the sliding-vane expander. A mechanical power of 17.4 kW is reached.
- During the second experimental campaign, some adjustments to the system have been implemented (increased insulation to avoid condensation, fine tuning of the lubricant injection system), leading to higher temperature and pressures of the steam flow during the test. Thanks to these improvements, a mechanical power of 28 kW is reached.
- The measurement of the pressure inside the expansion chambers let the calculation of the mechanical efficiency of the expander, that states around the 85%.

Future works will focus on the system improvement, with the implementation of an automatic control system, able to adapt the expander operation to the steam flow conditions.

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