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Experimental evidence of the thermal effect of lubricating oil sprayed in sliding-vane air compressors

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ABSTRACT

A way to increase the efficiency of positive-displacement air compressor is spraying the lube oil to exploit it not only as lubricating and sealing agent but also as thermal ballast. This work seeks the experimental evidence in sliding-vane compressors by measuring the air standard volume flow rate and the electrical power input of three diverse configurations. The first configuration, taken as the reference, employs a conventional injection system comprising calibrated straight orifices. The other two, referred to as advanced, adopt smaller orifices and pressure-swirl full-cone nozzles designed for the purpose; the third configuration utilizes a pump to boost the oil pressure. The laser imagining technique shows that the nozzles generate sprays that break-up within a short distance into spherical droplets, ligaments, ramifications and undefined structures. Tests on the packaged compressors reveal that the advanced configurations provide almost the same air flow rate while utilizing half of the oil because the sprays generate a good sealing. Moreover, the sprayed oil is acting as a thermal ballast because the electrical input is reduced by 3.5% and 3.0%, respectively, if the pump is present or not , while the specific energy requirement, accounting for the slightly reduced air flow, by 2.4% and 2.9%, respectively.
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1. Introduction

Positive-displacement machines are used widely for air compression in commercial and industrial applications. As in many other fields, the efficient utilization of energy has become a major goal. A way to increase the efficiency is spraying the lube oil into the gas as small droplets in order to exploit it not only as lubricating and sealing agents, but also as a thermal ballast with a great thermal capacity (thanks to its high density and heat capacity) and large exchange surface. In the past, Singh and Bowman [1] and Stosic et al. [2] analyzed numerically and verified experimentally the positive effect of sprayed oil on the shaft power of screw compressors, which was reduced by 2.8–8.3%. Over the years, other scientists achieved the same conclusions, despite a very few like De Paepe et al. [3] estimated benefits lower than 1%.

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This work seeks for the experimental evidence of the thermal effect of lubricating oil sprayed in sliding-vane air compressors, starting from the positive indications of a previous study [4]. Due to their cylindrical shape, sliding-vane compressors are particularly adequate because oil can be sprayed axially from the end plates. The compressors investigated here are electrically driven and packaged. Thus, the experimental evidence is sought by measuring the air standard volume flow rate and the electrical power input and by reconstructing the pressure-angle diagram (known as the indicator diagram) in a compressor equipped with either a conventional injection or an advanced spraying system. The advanced system is implemented in two configurations, depending whether an external pump is employed to boost the oil pressure.

2. Compressor configurations

The reference compressor is a large-size sliding-vane rotary compressor in which lubricating oil is inserted into the chambers with a conventional system comprising a number of calibrated straight orifices drilled on the stator.[1] Considering the compressor stator is a cylinder, the orifices are placed on the lateral surface, aligned along the axis, and positioned relatively close to the discharge port. Consequently, in the reference compressor oil is injected radially inward onto the rotor in a chamber in which air has already reached a high temperature due to the compression process. A pump is not required for this injection because the pressure of the oil after separation from the air is sufficient to sustain the injection.

The advanced compressors differ from the conventional by the way oil is inserted into the chambers. The diameter of the calibrated straight orifices is halved so that the flow rate through the orifices is roughly a quarter of the conventional. A number of pressure-swirl full-cone nozzles, specifically designed for the scope of generating small droplets at quite large flow rates,[2] are employed in addition to the calibrated orifices. A pressure-swirl nozzle is an atomizer that generates liquid droplets imparting a swirl motion to the fluid prior to entering an orifice so that the centrifugal forces break the fluid as soon as it leaves the orifice [5, Chapter 10]; the generated cone of droplets may be full (also said solid) or hollow.

The nozzles are mounted on the end plates and are distributed from the suction to the discharge port. Consequently, the oil through the nozzles is inserted axially in chambers in which air is increasingly reaching higher temperatures. Given the relatively large size of the nozzles, only up to four of them can be mounted on one end plate and none on the lateral surface where the calibrated orifices are. Two configurations of the advanced compressor are implemented: one configuration does not employ a pump, whereas the second uses a pump to boost the oil pressure exclusively for those nozzles positioned close the discharge port, where the air temperature and pressure are the highest. The flow rate of the oil through the nozzles is slightly less than a quarter of the conventional in the configuration without the pump, and slightly more with the pump. Briefly, the advanced configurations have an overall oil flow rate that is half of conventional; moreover, this flow rate is split almost equally between the calibrated orifices and the pressure-swirl nozzles.[3] The advanced compressor during the final stages of manufacturing are pictured in Fig. 1, whereas a schematic of the position on one end plate of the pressure-swirl full-cone nozzles (as well as of the piezoelectric pressure transducers, see below) is reported in Fig. 2.

3. Experimentation

Two different experimental campaigns are conducted. First, the nozzle sprays in an atmospheric reservoir are characterized at diverse oil pressures and temperatures with the laser imaging technique. A solid-state laser generates a monochromatic green light beam for the very short period of 5 μs that is directed into the spray. A camera captures the resulting scattering in photos that highlight the spray structure.

In the second campaign, the reference and the advanced compressors are tested on a rig that allows measuring:

- temperature, pressure and humidity of air at ambient conditions;
- temperature and pressure of air and oil along the process;
- pressure drop across an ISA 1932 nozzle;
- volume flow rate of oil through the external pump;
- rotational speed of the compressor;
- electrical power input to the package.

From the data, the actual delivered flow rate of air is computed accordingly to standard ISO 5167. Subsequently, the standard volume flow rate of air and the specific energy requirement of the packaged compressors are calculated accordingly to standard ISO 1217. The combined measurement uncertainty on the standard volume flow rate is in the 4.5–5.5% range (computed with the practical working formula of ISO 5167), the measurement uncertainty on the electrical

[1] The reference compressor is not a commercial unit because it employs modified inlet valve, suction port, discharge port and air–oil separator (see Fig. 1) that allow altogether an increase of air standard volume flow rate by 3.6%.

[2] The nozzles adopted here are different from the commercial ones analyzed in the previous investigation, [4], because they are tailored for the advanced compressor.

[3] A previous experience on a small-size compressor with calibrated straight nozzle and halved oil flow rate indicated that the performance decreased, so that this case is not investigated here on this larger unit.

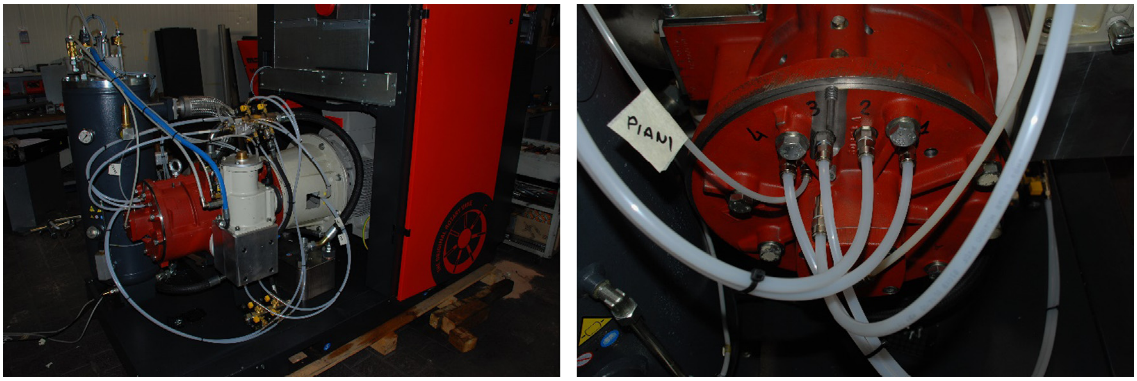

Fig. 1. Pictures of advanced compressor during the final stages of manufacturing. Left: overall system showing inlet valve (white in the front center), stator (red), air–oil separator (dark grey in the back) and electrical motor (grey in the cabin). Right: zoom over four of the pressure-swirl nozzles placed on one end plate of the stator, which are visualized on the schematic of Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

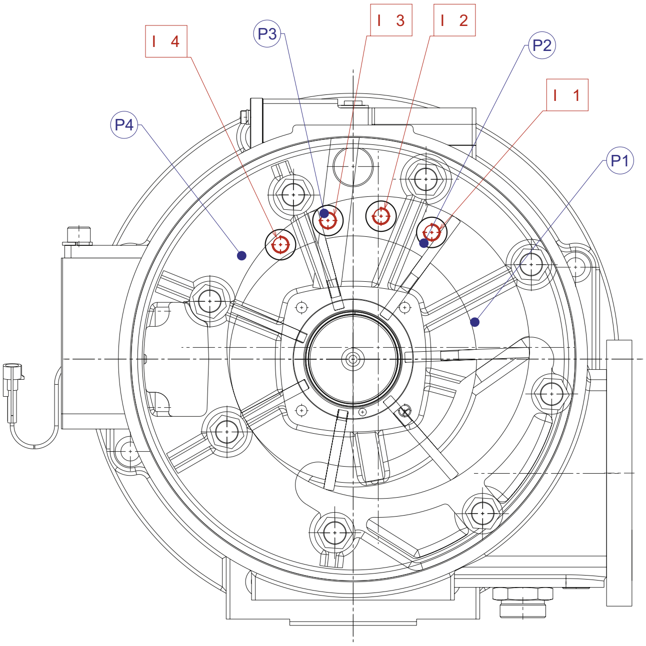

Fig. 2. Schematic of the position of the four pressure-swirl full-cone nozzles and of the four piezoelectric pressure transducers on one end plate (four nozzles are mounted also on the other end plate). Letter “I” indicates the nozzles, while “P” the transducers.

power input is at most 1% of the read value (the wattmeter belongs to the accuracy class 1%) and the combined uncertainty of the specific energy requirement is 4.6–5.6%.

Finally, all the compressor stators have four miniature piezoelectric pressure transducers placed circumferentially along one end plate. These transducers are used to measure pressure versus time. From the data acquired along 20–30 revolutions, the indicator diagram is reconstructed with the methodology developed by Cipollone et al. [6]. The measurement uncertainty of the transducers is 0.5% of the full scale of 25 bar.

4. Results and discussion

Regarding the nozzle characteristics, Fig. 3 highlights the spray structure for oil entering the nozzle at 6 and 14 barg and at 60 °C. These two conditions are representative for the spray without and with the external pump. The photos indicate that oil break-up takes place within a short distance from the nozzle in conditions that are typical for an air compressor. However, the spray does not lead exclusively to spherical droplets but mostly to ligaments, ramifications and undefined structures, as it was already observed in Ref. [4].

Regarding the performances, Table 1 reports the averaged measurements with respect to the reference compressor. Each compressor configuration is tested over three different runs to verify the measurement repeatability. The air standard

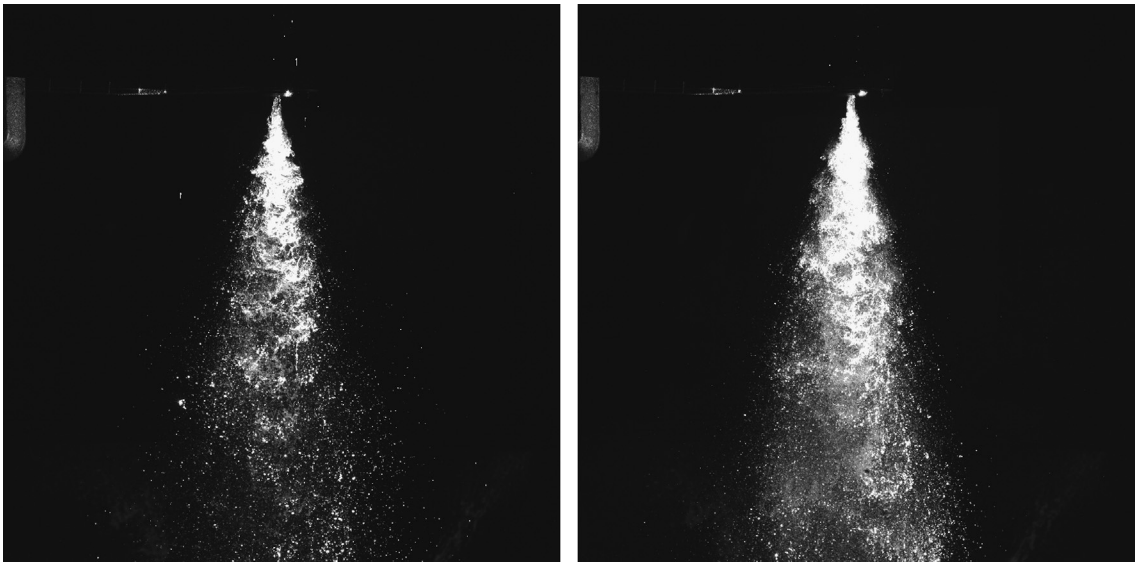

Fig. 3. Tests of the oil spray through the pressure-swirl full-cone nozzles captured with the laser imaging technique at two different pressures but same temperature of the oil. Left: 6 barg and 60 °C (representative of spraying without the external pump). Right: 14 barg and 60 °C (representative of spraying with the external pump).

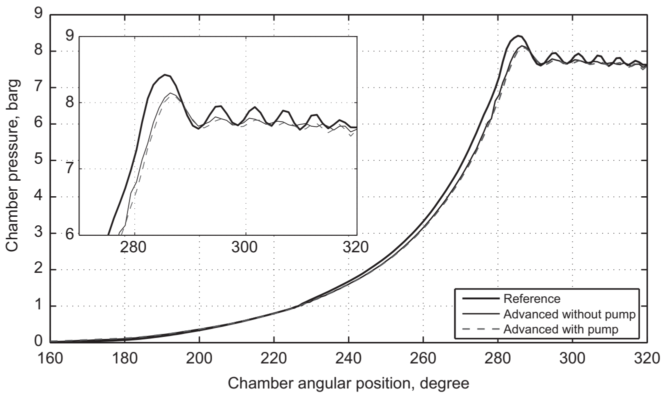

Fig. 4. Reconstructed pressure–angle diagram for the compressors in the conventional configuration and in the two advanced configurations, without or with the external pump for boosting the oil pressure. Outer: rotation from the suction port closing to the discharge port opening. Inner: zoom over the discharge port opening.

volume flow rate decreases by 0.6% (a negative reduction that is smaller than the uncertainty) despite the oil flow rate is roughly halved in the advanced compressors. The reason is that likely oil spraying generates a good sealing of the compression chambers that counterbalances its reduced flow rate. The electrical power input of the packaged compressor decreases with the oil spraying by 3.0 and 3.5% (a positive reduction that is larger than the uncertainty), if the external pump is not or is present.[4] The main reason is that oil spraying increases effectively the exchange surface and, hence, the heat exchange between air and oil permitting a better compression process. The use of an external pump allows increasing moderately the oil flow rate and simultaneously decreasing further the mean diameter of the droplets, or equivalently increasing further the exchange surface. However, the enhancement on the power input is only marginal. In its turn, the specific energy requirements of the advanced compressors, which accounts for the reduced air flow rate, decrease by 2.4% and 2.9%, respectively. These improvements refer to the package electrical input, which includes the power to the ancillary systems like fan, actuators and control system; thus, the improvements on shaft power are higher than the values reported above and are in agreement with the values reported by Singh and Bowman [1] and Stosic et al. [2]. Further improvements may be achieved in the future increasing the flow rate of the sprayed oil by decreasing the size of the nozzle allowing thus to increase the number of mounted nozzles.

[4] The value of 3.5% does not include the power input to the external pump because the pump employed in the experimentation is not specifically selected for the purpose, but it is actually oversized by far. In any case, the improvement is so marginal that it does not justify the installation of a dedicated pump.

Table 1
Average measurements for the packaged compressors in the conventional configuration and in the two advanced configurations, without or with the external pump to boost the oil pressure through the nozzles. Measurements are expressed with respect to the reference compressor. Each compressor configuration is tested over three different runs to verify the measurement repeatability.

Averaged measurements	**Configurations**		
	Reference compressor with conventional oil injection (%)	Advanced compressor with oil spraying and without a pump (%)	Advanced compressor with oil spraying and with a pump (%)
Air standard volume flow rate[a,b]	100	99.4	99.4
Electrical power input[b,c]	100	97.0	96.5
Specific energy requirement[b]	100	97.6	97.1

[a] According to standard ISO 5167.
[b] According to standard ISO 1217 referring to the packaged compressor (not to the bare compressor).
[c] Does not include the electrical power input to the external pump if present.

Fig. 4 reports the indicator diagram, which visualizes the variation of pressure as a function of the angular position of a chamber. The position of the chamber is defined here by the position of the trailing vane of that chamber. The process of the reference compressor (thick solid black line) at any given angle is above the processes of the advanced compressors (thin lines). The distance turns wider at higher angles (and greater than the uncertainty). This pressure difference is due to the effect of the air temperature on the chamber pressure: the lower the air temperature, the lower the chamber pressure. The reason for the lower temperature is that air warms up less rapidly in the advanced compressors because the sprayed oil is acting effectively as a thermal ballast. As clarified by the zoom close to the discharge port (inner chart of Fig. 4), the process with the external pump (thin dashed gray line) is only slightly below the process without the pump (thin solid black line) in agreement with the observation of a marginally lower energy requirement. Furthermore, the lower the air temperature, the lower the compression work, also in agreement with the lower energy requirements. Ultimately, the pressure oscillations at the discharge ports of the advanced compressors are limited compared to the reference compressor because the chamber pressure is lower when the ports open.

5. Conclusions

This work investigates experimentally the effect of spraying lubricating oil in part through pressure-swirl full-cone nozzles, as opposed to injecting in total through calibrated straight orifices, inside a packaged electrically-driven sliding-vane air compressor. The conclusions of the work are as follows:

- At typical air compressor conditions, a nozzle generates oil sprays that break-up within a short distance from the nozzle partly into spherical droplets and mostly into ligaments, ramifications and undefined structures.
- Oil spraying through nozzles generates a better sealing of the compression chamber allowing for a reduced oil flow rate while achieving almost the same air volume flow rate than injecting through orifices.
- Oil spraying increases effectively the heat exchange from air to oil during compression, permitting a process closer to isothermal and, hence, yielding a reduced electrical power input to the packaged compressor by 3.0%, without the use of an external pump.
- Boosting the oil pressure through the nozzle with a pump leads to a reduced electrical power input by 3.5% (not considering the pump electrical input), which is though a marginal improvement.

The future work will focus on decreasing the size of nozzle and thus increasing the number of mounted ones on the end plates to increase the oil flow rate and approach the optimal quantity of 10 kg of oil per kg of air indicated by the previous study [4].

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