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Experimental assessments on a pressure swirl oil atomizer for positive displacement vane compressors

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Abstract

The current work presents an experimental characterization of a pressure swirl nozzle that is used to spray the lubricant in positive displacement vane compressors such that the overall convective heat transfer between oil droplets and air is able to lower the specific energy consumption of the machine, bringing the closed volume compression phase towards an isothermal transformation. An experimental test bench was designed and built to reproduce the compressor operating conditions. Tests at different injection pressures and temperatures allowed to estimate some macroscopic features of the spray, namely break-up length and cone spray angle. In particular, measurements showed that while break-up length decreased at high pressure and temperature up to 3.1 mm at 65°C and 10 bar_g, the cone aperture tended to diverge from the nominal value of 80° up to 106°. Furthermore, measurements with a laser diffractometric particle size analyzer allowed to retrieve the droplet size distribution and to estimate a key parameter for the heat transfer capabilities of the spray, namely the Sauter Mean Diameter (SMD). At 55°C and 9 bar_g the droplet size distribution fitted a Rosin Rammler function with shape parameter of 1.87 and scale parameter of 228 μm while the spray SMD was 122 μm. In these operating conditions, a series of nozzles equally distributed along the closed volume compression phase of a mid-size industrial vane compressor would lead to specific power savings up to 0.3 kW/(m^3/min), that corresponds to 20-25% of the saving potential achievable considering an isothermal compression. This methodology will allow to calibrate a simulation platform of the sprayed injection technique such that further refinements of the energy saving strategy will be addressed.

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Keywords: droplet size distribution, laser diffractometry, pressure swirl nozzle, SMD, spray

1. Introduction

Reduction of energy consumptions and renewable energy production represent the most important pillars which will guide the future economy towards a new energy transition and a low carbon society. In this scenario, compressed air systems are responsible of 10% of the industrial electrical consumptions [1,2] which are, in turn, the 42% of the overall electrical consumptions [3]. In absolute terms, compressed air production in OECD countries accounts for 320 TWh. Among all the energy saving interventions that have been forecasted in the short term future, the saving potential that might be attributed to only a compressor upgrade was estimated in around 1% of the overall industrial electricity consumption, i.e. 3.2 TWh worldwide [4,5].

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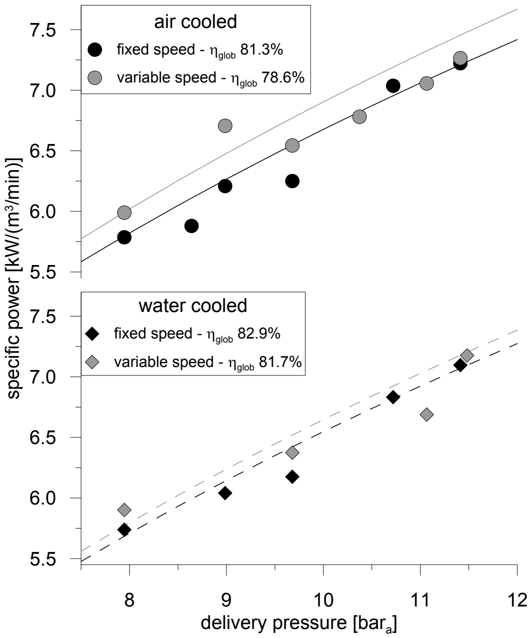

Fig. 1: Specific power consumption of best in class machines

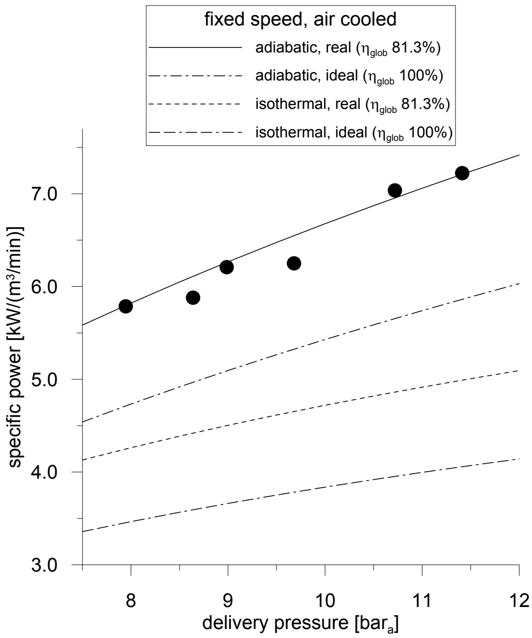

Fig. 2: Energy saving potential of an isothermal compression phase

Recent elaborations from energy performances of current air compressors fleets belonging to CAGI and PNEUROP manufacturers associations showed that, regardless of the delivery pressure, compressor efficiency increases with size (i.e. with flow rate): for air cooled machines, at 5 m^3/min, 20 m^3/min and 50 m^3/min, mean efficiency ranges around 65%, 73% and 82% respectively. In the same operating conditions, water cooled machines have an efficiency slightly higher. However, the large scattering that characterizes these statistical data demonstrates the coexistence of obsolete devices which still have a commercial interest as well as the room for a further compressor optimization [6,7].

In order to outline future energy saving strategies in industrial air compressors (that are almost exclusively positive displacement machines), statistical data of best in class machines at different delivery pressures reported in Figure 1 were fitted and compared to theoretical trends of specific power consumptions as occurs, for instance, in Figure 2 for fixed speed and air cooled compressors. Best in class machines have a global efficiency of 81.3% which also accounts for volumetric, electrical and mechanical losses. The distance in terms of specific energy consumptions at constant global efficiency between adiabatic and isothermal trends predicts a saving potential up to 1.5 kW/(m^3/min) at 9 bar_a. On the other hand, keeping an adiabatic compression and striving to improve the global efficiency through action on multiple areas whereas improvement potential has reached an asymptotic trend, might lead to savings up to 1 kW/(m^3/min) at 9 bar_a. Hence, it is evident that the most important contribution in order to increase the compressor efficiency is related to the thermodynamic one.

A suitable approach that has been pursued in multiple compressor technologies to orient the closed volume compression phase towards an isothermal process, was to spray the lubricant inside the compression volumes. In this way, the oil atomization led to a greater surface to volume ratio of the oil droplets and produced an air cooling which eventually reduced the indicated work.

In screw compressors, this energy saving concept was accomplished through numerical studies that investigated the heat transfer between oil droplets and air [8,9] as well as through experimental activities on the atomizers [10] or the whole compressor test rig [11]. In particular, in [12] the Authors stated a reduction on the energy consumptions from 2.8% to 7.4%.

Performance enhancement in sliding vane rotary compressors through a sprayed oil injection technology was achieved replacing plane orifice injectors with pressure swirl ones. Mathematical models and experimental campaigns on multiple compressors of different sizes showed that up to 6-8% of the specific consumptions can be saved [13–16]. Thanks to these real benefits, the effectiveness and reliability of pressure swirl injection technology has

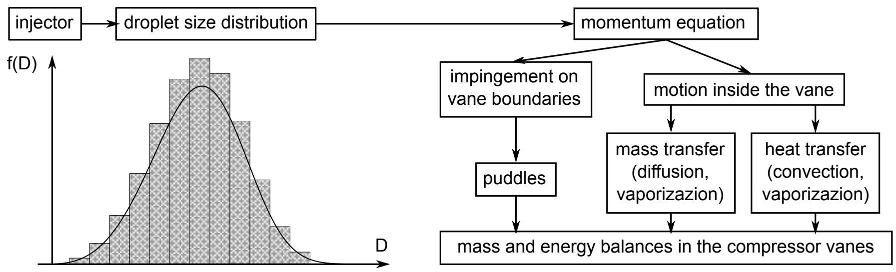

Fig. 3: Relevance of an accurate droplet size distribution for the overall reliability of the sprayed injection model

been transposed from prototypes to industrial machines and it is now supporting the development of a dual stage compression system [17].

In this paper, an experimental apparatus able to reproduce the injection conditions of a real compressor was developed to characterize the oil droplet size distribution of the above mentioned pressure swirl atomizers. The goal of the study was to validate a complex model previously developed by the Authors that, evaluating mass and energy exchanges between oil droplets and air during the closed volume compression phase, allows to estimate the energy saving benefits achievable with the sprayed injection technology for given injector and injection conditions [18,19]. Furthermore, a deep investigation of the atomizer features will allow to address future upgrades of the nozzles. Particle size measurements were carried out intersecting the spray with a laser beam and catching the forward scattered light in a plane detector whose light pattern can be associated to the droplet size distribution. This technique, known as laser diffractometry, is widely used in several contexts such as combustion, pharmaceutical applications, aerosols dispersion, rock characterization, sintered powders etc [20–22].
The paper presents some preliminary results of the diffractometric analysis which eventually allowed to calculate the experimental Sauter mean diameter and to estimate shape and scale parameters of a Rosin Rammler droplet size distribution that fitted the measurements.

2. Sprayed injection model

Downstream the break-up length of the oil nozzle, the droplets injected inside the compressor vane interact with the compressing air in terms of mass and energy exchanges: mass transfers may occur due to diffusive phenomena or, if saturation conditions are reached, due to vaporization. In this particular case, latent heat exchanges replace the more typical ones which take place due to forced convection between cold oil droplets travelling inside the warmer air. Mass and energy balances between oil droplets and air are solved with a Lagrangian approach whereas oil particles belonging to discrete diameter ranges propagate from the injector within its cone aperture.

A fundamental input to the sprayed injection model, that is schematized in Figure 3 and it is detailed in research works [16,18], is the droplet size distribution. Indeed, this curve provides remarkable information about the features of the oil spray such as the Sauter mean Diameter (SMD), which represents the diameter whose ratio of volume to surface area is the same as that of the entire droplet sample. Analyses showed that for heat transfer applications, only SMD can properly indicate the fineness of a spray and, in turn, its heat transfer potential. Hence, SMD is to be used to describe atomization quality [23].

In literature, several mathematical expressions were proposed to model droplet size distributions [21,24]. In the current model, the cumulative volume fraction distribution proposed by Rosin-Rammler was considered [25,26]. In particular, Eqns. 1 and 2 report the mathematical expressions of the cumulative distribution function $F_3(D)$ and the probability density function $f_3(D)$ that are both volume based. On the other hand, assuming spherical droplets, the number based probability density function $f_0(D)$ can be written as in Eqn. 3; if integrated between two diameters, $f_0(D)$ allows to calculate the number of droplets N contained in a specific size range.

$$F_3(D) = 1 - \exp(-(D/X)^q) \tag{1}$$

$$f_3(D) = \frac{q}{D}\left(\frac{D}{X}\right)^q \exp(-(D/X)^q) \tag{2}$$

$$f_0(D) = \frac{1}{N_{tot}}\frac{dN}{dD} = \frac{6\,q}{\pi D^4}\left(\frac{D}{X}\right)^q \exp(-(D/X)^q) \quad (3)$$

where $q > 0$ is the shape parameter and $X > 0$ is the scale parameter of the distribution. The value of X corresponds to the diameter for which the fraction of total volume of droplets smaller than X is equal to 63.2% (i.e. $F_3(X) = 0.632$) while q provides information on the spread of droplet sizes and typically ranges from 1.5 to 4, with higher values for more uniform sprays [23,27]. The total number of droplets N_{tot} that appears in Eqn. 3 can be evaluated knowing the mass of oil supplied to the injector.

Once the number based probability density function is known, the spray SMD can be calculated through Eqn. 4 that also presents a discrete formulation of the theoretical definition used to process particle size measurements.

$$SMD = \frac{\int_0^\infty D^3 f_0(D)\,dD}{\int_0^\infty D^2 f_0(D)\,dD} \simeq \frac{\sum_{j=1}^{J_{tot}} N_j\,D_j^3}{\sum_{j=1}^{J_{tot}} N_j\,D_j^2} \quad (4)$$

If experimental data are not available, in order to estimate SMD knowing the injector geometry (e.g. orifice diameter D_{or}, half of cone spray angle γ) and the thermophysical properties of the working fluid at the injection conditions (e.g. density of oil ρ_o and air ρ_a, oil dynamic viscosity μ_o, oil surface tension σ_o), several semi-empirical correlations were developed. Among them, the correlation used in the current model is reported in Eqn. 5 [28].

$$SMD = 4.52\left(\frac{\sigma_o\mu_o^2}{\rho_a\,\Delta p}\right)^{0.25}\left[2.7\left(\frac{D_{or}\,\dot{m}_o\,\mu_o}{\rho_o\,\Delta p}\right)\cos\gamma\right]^{0.25} + 0.39\left(\frac{\rho_o\mu_o}{\rho_a\,\Delta p}\right)^{0.25}\left[2.7\left(\frac{D_{or}\,\dot{m}_o\,\mu_o}{\rho_o\,\Delta p}\right)\cos\gamma\right]^{0.75} \quad (5)$$

At the state of the art, the model relies on Eqn. 3 (assuming q=3) to generate a Rosin Rammler droplet size distribution having a SMD equal to the one calculated through Eqn. 5. Nevertheless, a model calibration on the scale and shape parameters of the Rosin Rammler distribution would undoubtedly increase the accuracy of the overall simulation platform.

3. Experimental setup

The experimental facility is composed of an injection circuit and an optical unit and it is displayed in Figure 4. The first apparatus allows to reproduce the nozzle operating conditions that usually occur when it is installed in a rotary vane compressor. From an oil tank which is equipped with a controlled electric heater to set the injection temperature, the fluid is pressurized through a gear pump and firstly fills a small high pressure tank to reduce pressure fluctuations during the injection process. A throttled by-pass branch allows to regulate the oil flow rate that is delivered to the injection branch and measured by a turbine flow meter. A 3-axis nozzle stand hosts the oil atomizer which is instrumented with pressure and temperature transducers.

The diffractometric characterization of the oil spray that eventually led to its droplet size distribution was performed using a Malvern Mastersizer X granulometer shown in Figure 4.b. The optical setup comprises a He-Ne laser (wavelength 633 nm) and a beam expander which performs a polarization of the laser beam to be perpendicular to the scattering plane. When oil droplets interact with the parallel beam of monochromatic light, as in Figure 4.c, a diffraction pattern is formed: large particles scatter light at small angles relative to the laser beam while small particles scatter light at large angles. In this way diffraction patterns are formed. Afterwards, a Fourier transform receiver lens focuses the diffraction patterns onto a multi-element photodetector that measures the light energy distribution. The photodetector consists of 31 semicircular photosensitive rings surrounding a central circle. Each ring is most sensitive to a particular small range of droplet sizes. The measured light energy distribution is then converted to the droplet size distribution using a post-processing algorithm based on the Fraunhofer approximation of the Mie theory, which allows to derive droplets diameters from light intensity assuming volume-equivalent spheres but regardless of optical properties of the sample.

The working fluid is a Mattei Rotoroil 8000F2 with specific gravity of 0.95, kinematic viscosity at 40°C equal to 99 cSt and to 10.2 cSt at 100°C.

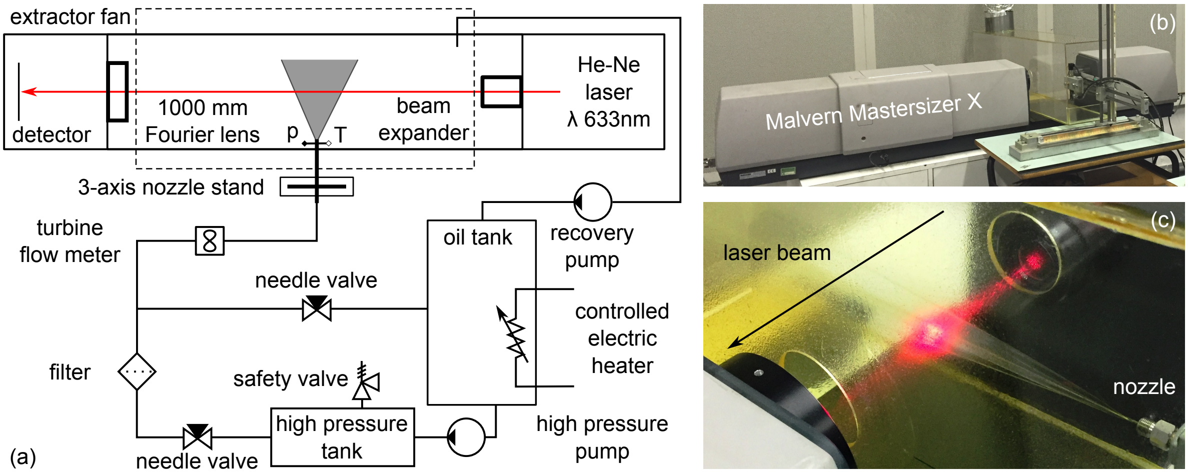

Fig. 4: Experimental apparatus: (a) optical setup and injection circuit layout, (b) test bench, (c) interaction between spray and laser beam

4. Results and discussion

The macroscopic features of the oil sprays produced by the pressure swirl atomizer were characterized processing the images taken with a camera such that the break-up length and the cone spray angle could be measured. The exposure time of 0.125s was sufficiently long to provide a suitable visualization of the overall spray. Indeed, this methodology provides the time-integrated effects of the spray and therefore is not appropriate to measure the droplets size. Tests were carried out at multiple injection pressures and temperatures and are synthetized in Figure 5. The frames series reported in Figure 5.a show an increasing brightness of the spray region when injection temperature and pressure increase. Both the effects are due to finer atomization processes that enhance the light scattering of the oil particles. However, while the injection pressure is actually the driving force of the atomization, the oil temperature acts on the dynamic viscosity and on the surface tension of the fluid to enhance the primary break-up of the oil jet. From 45°C to 55°C, oil temperature also affected the overall flow pressure drops in the injection circuit and, in turn, the flow rate supplied to the nozzle, as revealed by the measurements reported Figure 5.b.

The break-up length of the spray, i.e. the distance from the nozzle orifice that the liquid jet requires to achieve an atomized regime of droplets, was measured considering the length of the segment from the outer boundary of the nozzle up to the edge point that the straight oil jet and the spray cone create. Afterwards, the picture resolution of 42 pixels/mm was considered as calibration law to express the measurements in millimeters. Figure 5.c shows that break-up length decreases with injection pressure and temperature. At 55°C, break-up length shortens from 4.3 mm at 6 bar_g to 3.3 mm at 10 bar_g. On the other hand, for a given injection pressure of 9 bar_g, an oil temperature of 45°C, 55°C, and 65°C brings it to 3.7 mm 3.5 mm up to 3.3 mm respectively. When installed on sliding vane compressors, the upper limit of the propagation length of the spray is the axial length of the machine which is one or two order of magnitudes greater than the break-up lengths revealed experimentally. Therefore, pressure swirl technology leads to sprays whose development inside the compressor vane can effectively contribute to perform an air cooling. This fact does not apply for conventional injectors which are straight calibrated holes that supply the amount of lubricant required to the machine to fulfill lubrication and sealing as liquid jet. Hence, in this case there is no break-up.

Another relevant parameter for the effectiveness of the oil spray injection in vane compressors is the cone spray angle. Indeed, if the cone aperture is greater than the gap between rotor and stator, oil droplets would suddenly impinge on the metallic surfaces of the compression cell and lead to the formation of oil puddles which do not contribute to a convective heat transfer with air. In order to assess this issue, cone spray angle measurements were performed on the image series of Figure 5.a and reported in Figure 5.d. The half of cone spray angle was measured considering the spray axis and an averaged generatrix of the lateral cone surface. At high injection pressures and temperatures, the cone aperture tends to diverge: at 65°C and 6 bar_g, cone spray angle is 84°, close to the nominal value of 80°. When injection pressure raised up to 10 bar_g the cone angle became 106°.

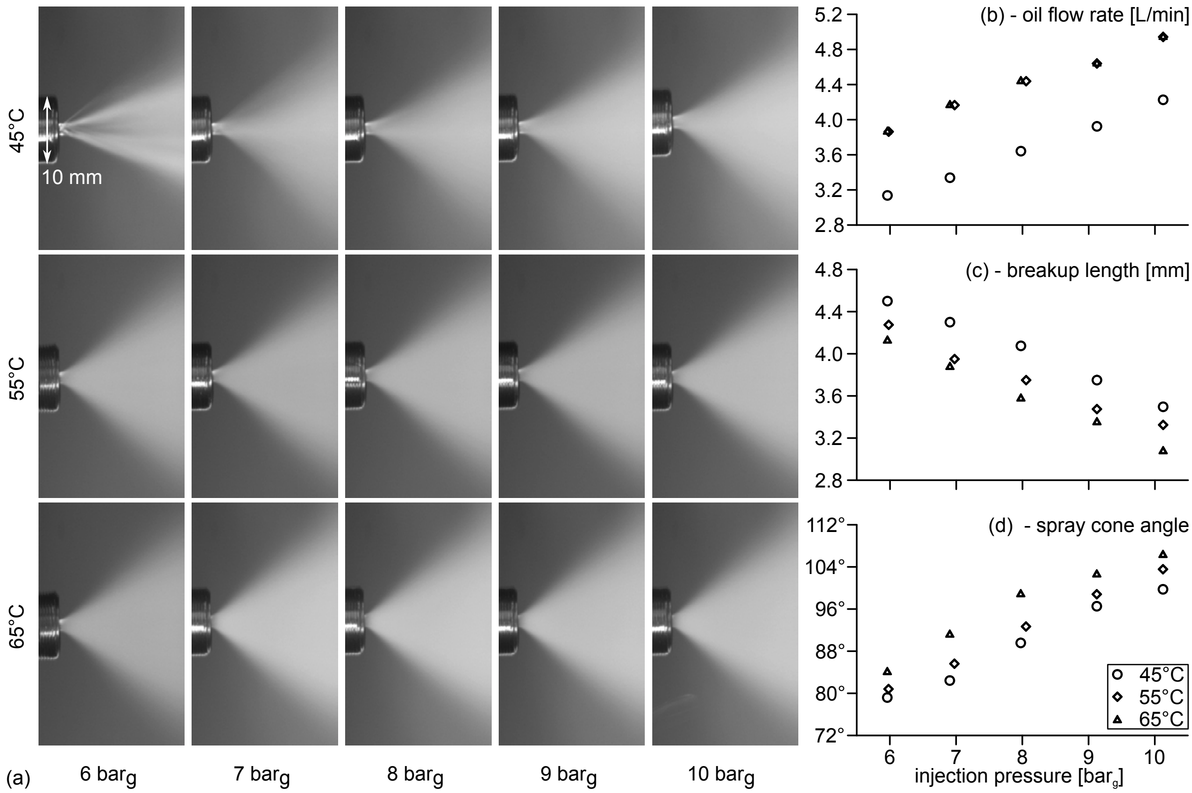

Fig. 5: Spray break-up at different injection conditions: (a) photographs taken with Canon EOS 40D camera and 70-120 mm objective using an exposure time 0.125s and ISO 1600 - image resolution 42 pixels/mm, (b) oil flow rate at the injection conditions (uncertainty 3% of the measured value), (c) measured break-up length, (d) measured spray cone angle

A deeper investigation of the spray features provided by the oil pressure swirl atomizer was eventually carried out using the laser diffractometric technique. The information provided by the cumulative volume fraction distribution displayed in Figure 6 allowed to calibrate the Rosin Rammler distribution model. With reference to Eqn. 1, the deviation between experimental and numerical data was minimized considering a scale parameter of 228 μm and a shape parameter of 1.87.

Additionally, Figure 7 reports the experimental probability density functions at 55°C and 9 bar_g. The number based distribution shows that a remarkable amount of droplets is concentrated below 10 μm but their contribution becomes negligible in terms of overall volume of the spray sample. The Sauter mean diameter, computed according to Eqn. 4, was eventually equal to 122 μm. This value is in agreement with the semi-empirical correlation that was implemented in the oil injection model (Eqn. 5) that yields to a SMD of 131 μm considering a nozzle orifice diameter of 1.6 mm [29].

Installing a series of five pressure swirl atomizers equally distributed along the closed volume compression phase of the mid-size sliding vane machine tested in [16], oil sprays with a SMD of 120 μm would be able to exchange with the compressing air a thermal power up to 1 kW and, in turn, to lower the specific consumptions up to 0.3 kW/(m^3/min). Therefore, if one compares this performance with the theoretical predictions reported in Figure 2, it can be concluded that a sprayed oil injection technology in sliding vane compressors is currently able to reach up to 20-25% of the intrinsic saving potential of an isothermal compression phase. Conversely, this remarkable result would be barely achievable acting on an advancements in terms of global compressor efficiency. Indeed, since mechanical and electric efficiencies of the compressor and the electric motor have reached very high values, a further increase of these parameters would imply investment costs that would hardly be feasible from an economic viewpoint.

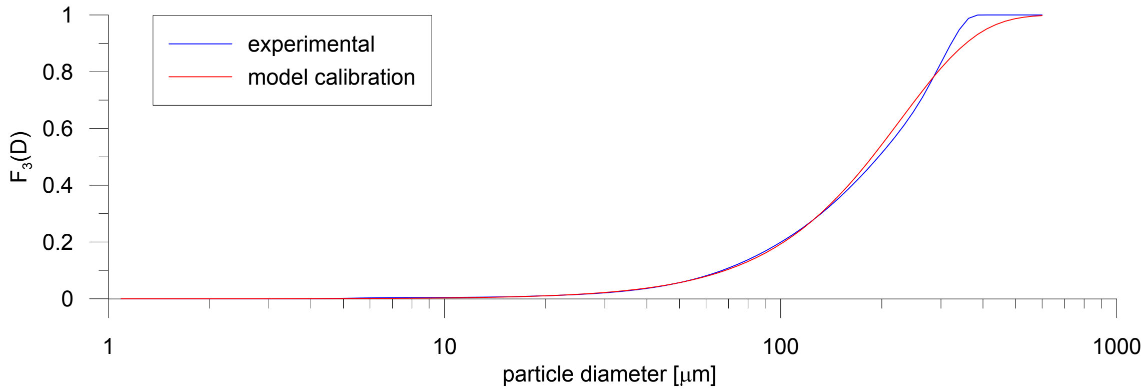

Fig. 6: Calibration of the Rosin Rammler cumulative volume fraction distribution (Eqn. 1) - shape parameter 1.87, scale parameter 228 μm

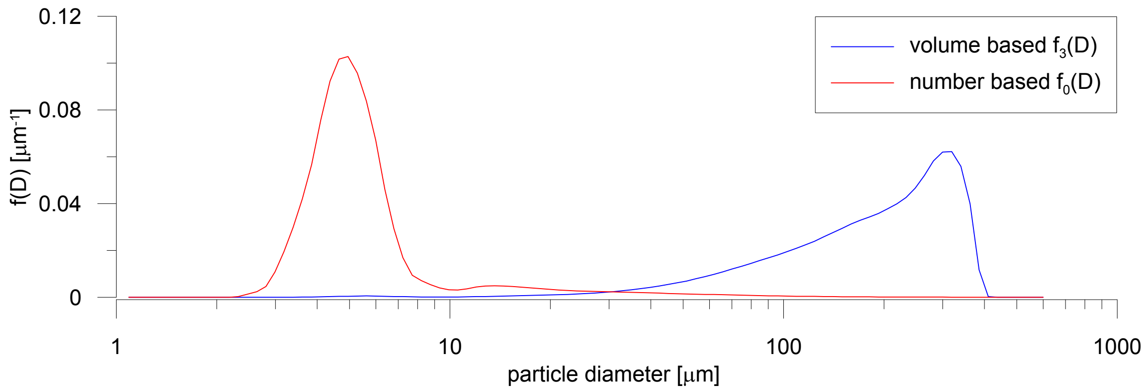

Fig. 7: Experimental probability density functions at 55°C and 9 bar_g - the spray Sauter mean diameter (SMD) is 122 μm

5. Conclusions

Oil sprayed injection technology revealed a noteworthy strategy to lower compression work in positive displacement machines such as sliding vane compressors. The heat transfer capabilities of a spray can be synthetized through the Sauter mean diameter (SMD). Even though semi-empirical correlations are available in literature to estimate the spray SMD for given injector geometry and operating conditions, a more accurate approach is its derivation from the droplet size distribution.

For this reason, the current research work investigated a pressure swirl oil atomizer for vane compressors through multiple experimental methodologies. A test bench was built to simulate the injection conditions that occur in real industrial air compressors. The oil sprays delivered by the injection circuit were firstly analyzed through a photographic approach to evaluate some macroscopic features of the spray at different injection conditions, namely brake-up length and cone spray angle. In particular, injection pressure and temperatures lowered the brake-up length enhancing the primary brake-up mechanism and, at the same time, led the cone spray aperture to diverge.

Furthermore, using a laser diffractomeric technique, a preliminary particle size analysis allowed to retrieve the droplet size distribution which fits a Rosin Rammler function with shape parameter of 1.87 and scale parameter of 228 μm. The Sauter mean diameter of the oil spray at 55°C and 9 bar_g was 122 μm. In this conditions, when installed on vane compressors, the oil sprays would lead to specific power savings up to 0.3 kW/(m^3/min), which is the 20-25% of the total share achievable through an isothermal compression.

These results demonstrate the scientific rigour of the experimental approach which will be further enhanced through a full injector characterization. In this way, a calibration of the existing simulation platform for the oil sprayed injection technology will be performed to address improvements to the compressor energy saving technique.

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