EXPERIMENTAL MEASUREMENTS USING SHADOWGRAPH SYSTEM ON THE SCREW COMPRESSOR

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Oil-lubricated gas compressors and other machinery generate a fine, mostly submicron droplet aerosol (''oil mist''), which is typically captured and removed by microfiber filter media. Such filters are designed to coalesce and drain the accumulating oil continually in order to maintain a steady mode of operation. Particle Image Shadowgraph (PIS), an accurate and efficient technique, is employed to determine the particle size probability distribution and particle diameters to contribute to a better understanding of the complexity of the formation of oil droplets suspended in the compressed gas.

Keywords: Shadowgraph, Sauter Mean Diameter (SMD), Oil-lubricated screw compressors

1. Introduction

Oil-lubricated screw compressors are mainly used in industry to provide compressed fluid (air, natural gas, etc.) for various applications. The compression process in this type of compressors leads to the formation of oil droplets suspended in the compressed gas that need to be separated from the gas phase in order to comply with the purity requirements in operation and transport. It is assumed that the particle size distribution (PSD) of oil droplets at screw compressor discharge ranges between 40 nm- 500 μm. Droplets between 10 - 500 μm are separated using knitted mesh, guide vane, or centrifugal methods. To remove oil droplets smaller than 10 μm, also known as oil aerosol or oil mist, fibrous glass filters are used. Mead-Hunter et al. (2014) [1] give a good overview of the extensive investigations that have been carried out regarding fibrous glass filters. Other research [2, 3] concentrates to a large extent on the droplets entrainment from oil mist coalescing filters. Penner et al. (2019) [4] showed recently that the penetration of oil mist filters was strongly correlated the properties of the media through which the liquid is transported. According to their experimental results, the residual oil content, under steady state operating conditions, was significantly dependent on the operating conditions of the filter. Simon Kaiser et al. (2019) [5] conducted an experimental study to determine the

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particle size distribution by combining an optical particle counter (OPC) with a scanning mobility particle sizer (SMPS), the particles size being in the range of 40 nm - 3 μm. Detailed insight into the liquid transport mechanisms taking place inside such filter media [6,7] reveals that coalesced oil is not able to drain internally by gravity because the microfiber matrix is too dense, but rather from the downstream filter face where it is transported to by the airflow. Aside from engineering studies, there is abundant scientific literature on the microphysics of liquid film break-up with related descriptive models [8, 9, 10]. What we observed from there is that predominantly small droplets (< 10 μm) are sheared off and entrained into the gas flow when a liquid film is relatively thick and the gas velocities are high [11], whereas larger drops (> 100 μm) are generated in case of thin liquid films and/or low gas velocities [12].

Continuous research and development have allowed this type of screw compressor to find a position on the market, the range of sizes diversifying in a much more explosive way than any other type of compressors in the last decade. It should be mentioned that the oil introduced into the compressor always remains in liquid phase, and thus has a high cooling capacity. The volume occupied by the oil is less than 0,5% of the gas volume and there can be no situation leading to forcing the compressor to compress the oil. Separation of oil from gas, after the compression stage, is necessary both to ensure proper gas quality and to reduce oil consumption. The gas-liquid separation equipment is used to retain most of the oil droplets mixed with compressed gas. The efficiency of the gas-liquid separator depends on gas velocity, oil mass rate, oil type, oil droplets dimensions, discharge pressure, and temperature. During the operation of this type of compressor, many equipment operators reported a loss of oil through the discharged compressed gas that can lead to faulty functioning of the equipment, thereby increased operating costs and contamination of the working environment. These situations generally occur when the operating parameters of the compressor package change or when the separation systems are not chosen properly for the application. To determine the fractional separation efficiency of the oil-gas separation system, the Sauter Mean Diameter (SMD) [14] of the oil droplets which are present in the discharged gas must be determined through an experimental campaign based on shadow imaging.

2. Experimental setup

The oil aerosol generator used for this experiment was a screw compressor package ECS30/10 equipped with an oil-lubricated screw compressor. The compressor was driven by an asynchronous electric motor, controlled through a variable speed drive (VSD). The screw compressor has asymmetric helical rotors with a distance between axes of 180 mm.

The main elements of the ECS 30/10 package, installed on a metallic structure, are the screw compressor, the electric motor, the separator vessel, the lubricating oil pump system, the oil cooler, the gas and oil filters, the command and shut-off valves and various measuring and protection devices (Fig.1).
The oil system contains a lubrication pump and all the circuits that ensure the lubrication of the bearings and the cooling of the compressor. Screw compressor packages can operate with discharge pressure under 4.5 bar (g) [13]. Otherwise, a minimum discharge pressure of 4.5 bar (g) is required for proper oil injection in the compression process. To control the oil mass flow injected in the compressor the oil pump speed needs to be adjusted. The oil-gas separation system is a vertical pressurized vessel and it is used to separate the oil from the compressed gas.

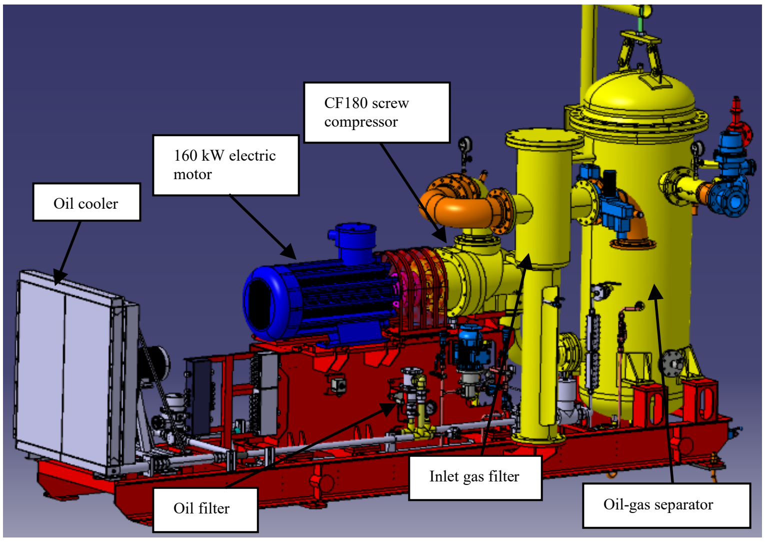

Fig.1. Screw compressor package used for oil aerosol generation.

Table 1

The screw compressor characteristics

Parameter	Symbol	Value	Unit
Molar weight	M	28.29	kg/kmol
Suction temperature	T_1	15	°C
Suction pressure, absolute	P_1	0.95	bar (a)
Suction pressure, gauge	$P_{1,r}$	-0.05	bar (g)
Male rotor speed	n	2420	rpm
Volumetric flow/day	Q_g	35559	Nm^3/day
Volumetric flow/hour	Q_h	1481.6	Nm^3/h
Suction volume flow/hour*	V_1	1643.4	m^3/h
Suction volume	V_a	0.025	m^3/rev
Mass flow/h	M	1916	kg/h

Mass flow	Ma	0.532	kg/s
Discharge pressure, absolute	p_2	4.5	bar
Compression ratio	π	4.74	-
Discharge temperature oil&gas	t_2	80	°C
Oil temp after cooler	t_{ui}	45	°C
Oil volumetric flow	Qu	81.04	l/min
Oil mass flow	M_u	1.18	kg/s
Gas constant	R	286.9	J/kg*K
Consumed power	P	115	kW

*Corrected at inlet pressure and temperature

The separator is used also as an oil tank. The oil-gas separation system is made of two stages: one stage using the centrifugal effect and the second one consisting of a knitted stainless wire mesh. Downstream of the vertical oil-gas separator, an oil coalescing filter is mounted.

The measurements were carried out under steady state conditions after a warm-up period. Typical temperatures at the compression unit outlet were around 80 °C. All the experiments were conducted at a constant volumetric flow rate of 1481 m^3/h.

For natural gas compression applications, synthetic hydrocarbon lubricants such as poly-alpha-olefin (PAO) and poly-alkyl-glycol (PAG) based oil are used [13]. For this application, Dacnis H68 mineral oil was used. In *Table 2*, the relevant oil characteristics are shown.

Table 3

Main oil characteristics at distinct temperatures

Parameter	Value			Unit
Temperature T	40	50	90	°C
Density $\boldsymbol{\rho}$ (kg/m^3)	869	866	821	kg/m^3
Cinematic viscosity $\boldsymbol{\nu}$	58	36	10.5	$m^2/s \cdot 10^{-6}$
Dynamic viscosity μ	50	31	8	$kg/ms \cdot 10^{-3}$

Fig.2 Shows a diagram of the experimental setup. The aerosol is generated by the oil-lubricated screw compressors.

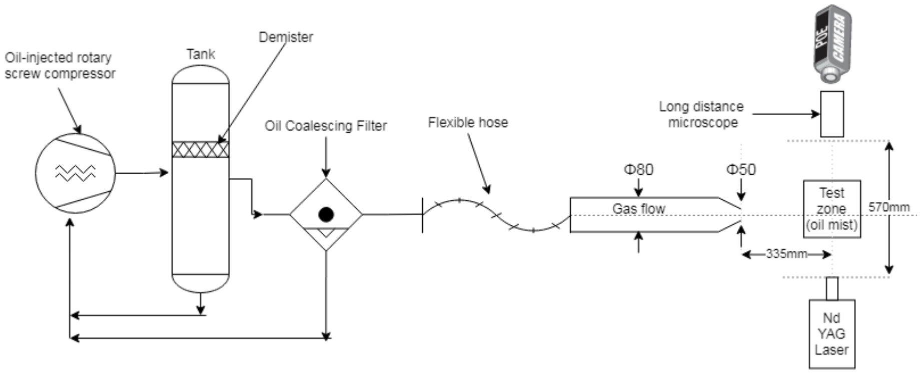

Fig.2. Experimental setup.

2.1 Shadowgraph system

The shadowgraph (backlighting) [14] technique is a non-intrusive optical imaging method for particle sizing which is independent of the observed particle's shape and nature. It is a point measurement method that consists basically of a light source and a detector, such as a long-distance microscope coupled to a high-resolution CCD (Charge-Coupled Device) [14].

The diameter of the shadow produced by droplets is measured in a thin focal plane determined by the depth of field of the microscope where the droplets are illuminated from behind. To perform a backlight-illuminated particle sizing measurement, the illumination, the target, and the detection system have to be aligned (as shown in Fig. 3). For illumination, a diffused, wavelength laser beam from a pulsed frequency-doubled Nd:YAG laser (λ= 532 nm) was used.

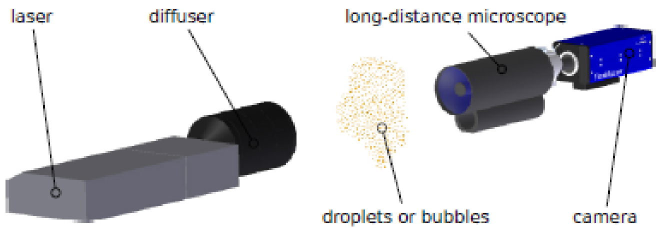

Fig.3. Experimental setup for measurement of particle size distribution with Particle Master Shadow [14]

The use of a pulsed laser source and double exposure recordings permit simultaneous measurements of the size and velocity of individual droplets in a small region of the spray. The image acquisition section consists of a CCD double-frame camera (IMAGE PRO X 4M). To minimize the error during counting, numerical algorithms are used to complete a statistical count of recorded droplet samples from an experiment. The Particle Master Shadow Software 10.0.5

algorithm is used to detect, measure, and count the recorded images of droplets. A threshold two-step segmentation algorithm [14] is applied to the recorded images. The first segmentation serves to locate the droplet, and then those segments are analyzed separately for size, shape, and position in the second step.

2.2 Calibration and processing aspects

The DaVis software [14], used for this work, is based on image analysis. In the first step, a global intensity separates particle images from the background. In the second step, the user has to define two local threshold levels, which are used to segment valid particles and determine the respective particle properties (area, diameter, intensity gradient, etc.).

For velocity computation, a particle matching between the double-frame images is required. Furthermore, several aspects need to be taken into consideration when performing particle sizing using a shadow imaging setup.

First, there is the requirement of camera calibration, scaling the real world to image dimensions. This was conducted by inserting a calibration target featuring distinct markers with known distances as exact as possible at each measurement position, the front of the calibration target positioned parallel to the mid-depth plane of the flow.

This procedure also ensured an appropriate alignment of the focus plane of the cameras to the measurement plane. The calibration plate was used to mark off the field of view (FOV), which is presented in Fig. 4.

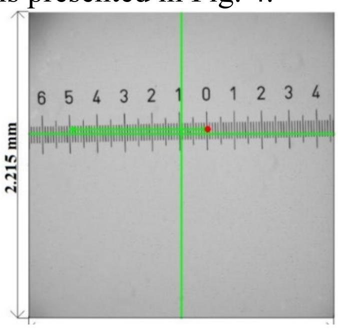

Fig. 4. Calibration plate - a square with side of 2.215 mm (FOV=4.906225 mm^2)

The image processing, using DaVis software, is based on determining the location of particles in an area of interest, and on the subsequent analysis of their position in each frame. The displacement of particles between two consecutive frames is used to calculate the velocity of the particle, as shown in Fig. 5. Recognition is based on difference in the intensity of the image.

The shadow imaging camera does not only record focused particle shadows but also out-of-focus shadows, particles that are not exactly located in the focus plane of the camera. Consequently, the perimeter detection becomes harder and the detected diameter deviates considerably with increasing defocusing [9]. It is also usually not practical to consider all the imaged particles.

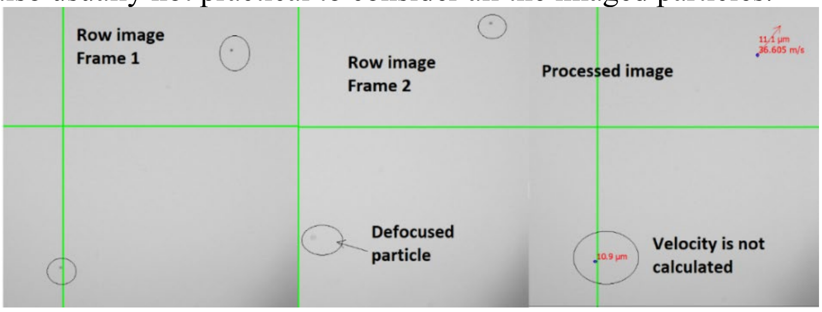

Fig. 5. Post processing steps

These reasons motivate an algorithmic restriction to exclude particles above a certain defocusing level from further processing. The procedure carried out by the software in this respect is described in Figure 5. Once the experimental images have been processed, the software will display the size and velocity of all particles.

3. Results

The process undergone by the oil particles during screw compressor operation can be divided into two stages. In the first stage, the oil stream breaks into droplets under the influence of the kinetic energy of the air. In the second one, mixing of the aerosol with a stream of heated air takes place. As a result, a thermo-aerosol with a constant temperature is obtained. Obviously, in both stages, evaporation of aerosol droplets occurs. Away from the pipe nozzle, the droplet velocity decreases, the spray is diffused, and the possibility of droplet coalescence is reduced.

Based solely on the analysis of the mechanism of the atomization process, determining the number and diameter of droplets in a theoretical manner is not possible. Droplet sizes depend on controlled and uncontrolled factors. Controlled factors include, among others: the atomizer geometry and the fluid type. Uncontrolled factors are, for example, disturbances and vibrations.

To obtain meaningful information on the size and distribution of the oil droplets, experimental investigations, and statistical analysis of the data, such as those presented here, two sets of experimental results are presented: with and without the coalescing filter.

During the experiment, 300 double images were captured by the CCD camera for post-processing in order to provide the diameter and velocity of particles (Table 3).

Table 3

Parameter overview

Parameter	Value	Unit
Outlet diameter	50	mm
Outlet area	1963,4954	mm^2
Amount of oil	0,0125	mg/s
Density of oil	0,9	mg/mm^3
Reference diameter of oil particles	10	µm
Volume of one particle	5,236E-07	mm^3
Number of particles in one second	26525,762	-
Average velocity	11	m/s
Spray volume	0,1	m^3
FOV (Field of View)	4,906225	mm^2
DOF (Depth of Field)	0,1	mm

A mean value provides some information of the sizes present, but does not issue any indication about the distribution's shape or how broad or narrow it is.

The Sauter Mean Diameter (SMD-D32), a statistically obtained droplet size, has been widely used [9] for an objective evaluation of atomized droplets. Table 4 presents the PSD obtained cumulated statistics: Dv10 - Arithmetic average of the particle diameter; Dv10, Dv50, Dv90 - Volume percentiles at 10 %, 50 %, 90 % (Dv50 means that all particles with a diameter up to Dv50 contain 50% of the total particles volume).

Each particle has the same contribution to this average, only corrected by its statistical weight to compensate for a detection bias. As a result of the experiment, we obtain particles of various dimensions, and their distribution is called the atomization spectrum or histograms.

Table 4

Cumulated Statistics for tests with and without coalescing filter

	Statistic	Value (with filter) 18 particles	Value (without filter) 45 particles	Unit
1	D10	6.2	6.4	µm
2	D32	9.9	9.8	µm
3	Dv10	5.9	6.6	µm
4	Dv50	11.1	10.8	µm
5	Dv90	14.9	12.2	µm

To illustrate the sizes that exist, the size range is split into small size classes or “bins”, and the number of particles contained in each size bin is counted.

Fig. 6 and Fig. 7 presents, in red, a size histogram of the actual particle distribution for the case with no coalescing filter, respective with coalescent filter, while the green line represents the cumulated distribution of the particles.

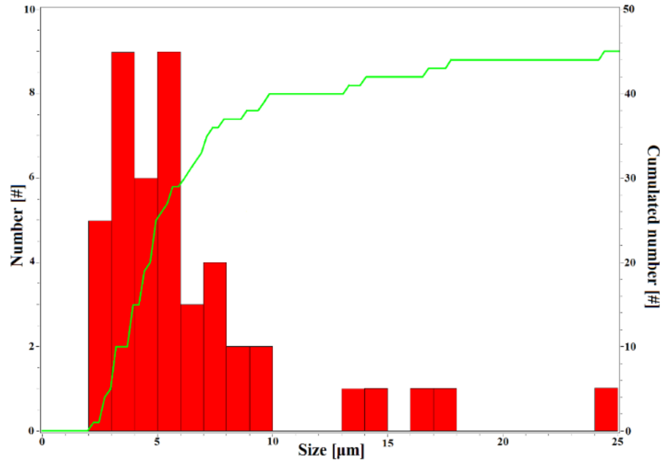

Fig.6.Histograms for tests without coalescing filter

In Fig.8 are represented both histograms.

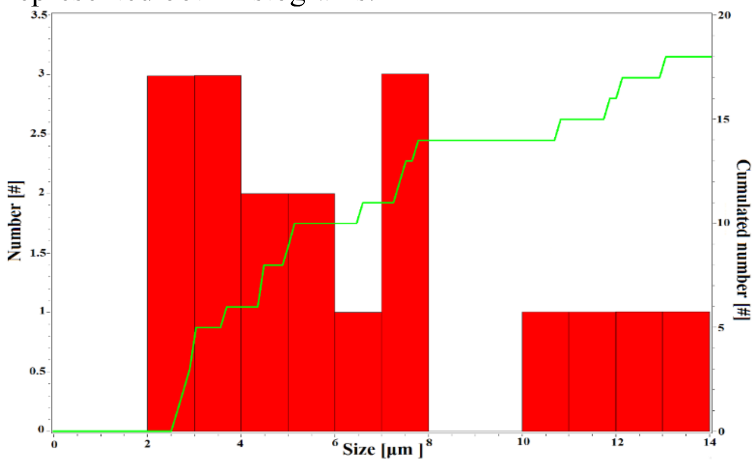

Fig.7. Histograms for tests with coalescing filter

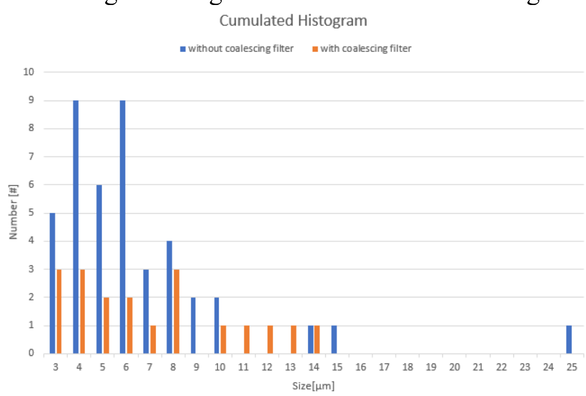

Fig.8. Cumulated Histogram

4. Conclusions

In this research work, droplet size distributions are investigated through experimental methods. The results of this research contribute to a better understanding the process of leaking oil from the compressor and the process of disintegration of oil particles in the exhaust pipe and can help design both screw compressors and coalescing filters.

During the experiments, a decrease in the number of particles, as well as their maximum diameters was detected when the coalescent filter was used.

The Particle Image Shadowgraph (PIS) is proven to be an important experimental tool and can help in the design process of oil-lubricated screw compressors and coalescent filters. Additional advantages include high image quality, low cost of experimental setup and easy to use.

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