A laser diffraction study on droplet diameters in two lubrication systems

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Abstract Laser-based techniques for particle-size measurements become widely used, as they are non-intrusive measuring methods. As droplet distribution becomes of importance in heat exchange processes, two-phase flow pressure drops, pipe corrosions, manufacturing processes and research activities, online control of this distribution with laser diffraction systems is really helpful. This paper presents a comparative study of the usability of laser diffraction systems to measure different range of flow rates and conditions for two lubrication systems (minimum quantity cooling for cutting tool lubrication and aero-engine de-oilers). Droplet size measuring systems are presented, and a comparison between results obtained with the Sympatec Helos-Vario/KR laser diffraction and a particle dynamics analysis system is discussed. The two systems are used on two different test benches and have different measuring conditions (spray and annular flows). The measuring method developed to extract the droplets from the film of the annular flow is discussed and the working conditions are presented in function of a parameter chosen to characterize the usability of laser diffraction methods. Droplet distribution and Sauter mean diameter results are then presented in function of different key parameters and compared to theoretical studies. The results showed a good agreement between theory and experiments in the limit of the theoretical working conditions. They also showed the need for new semi-empirical correlations to be developed for our working conditions. The tests showed that the limits of these systems are reached for small droplets as the limit in working distance is reached. For high liquid mass flux, the amount of droplet increases and lead to multiple scattering and complicated measurements. Spray applications, on the other hand, showed easy and repeatable results. Some other applications should be tested in order to confirm those results.

Nomemclature

Symbol		Sub/Superscripts		Acronym	
$\dot{m}$	Mass flow rate	l	Liquid phase	LD	Laser diffraction
$\dot{q}$	Volumetric flow rate	g	Gas phase	PDA	Particle Dynamics Analysis
σ	Surface tension	r	Air relative to liquid		
ρ	Density			SMD	Sauter Mean Diameter
n	Spread parameter	M	Maximum value	PASS	Pump and Separator System
n_l	Refractive index	m	Minimum value		
d	Diameter	s	Superficial	MQC	Minimum Quantity Cooling
μ	Dynamic viscosity				
u	Velocity			MQCL	Minimum Quantity Cooling Lubrication
p	Pressure				
$\phi_{l/g}$	Volumic liquid gas ratio				
We_c	Weber number				
e	Entrainement rate				

1. Introduction

Laser-based techniques for particle-size measurements become widely used, as they are non-intrusive measuring methods. As droplet distribution becomes of higher and higher importance in heat exchange processes, two-phase flow pressure drops, pipe corrosion, manufacturing processes (Black 1996) and a lot of research activities, online control of this distribution with laser diffraction systems is really helpful. Nevertheless, some discuss the accuracy of those systems (Etzler 1997) and as their use can be complicated, a good understanding of the working principle of the laser and the application may be needed to correctly interpret the results.

The aim of this paper is to present a study of the usability of laser diffraction systems to measure droplets for a large range of working conditions. This will be illustrated, from a user point-of-view, by two applications where the droplet size distribution is of importance. The Aero-Thermo-Mechanics Department (ATM) of Université Libre de Bruxelles (ULB) is currently developing two different devices used in lubrication systems. The first one is a Minimum Quantity Cooling (MQC) airblast injector for machining purposes of metallic and non-metallic materials. The second is an innovative device that simultaneously separates and pumps an oil-air mixture for aero-engine lubrication systems (Gruselle 2011). Oil droplet sizes are of a crucial importance in both applications. For MQC applications, the cooling effect depends on the droplet size distribution, which changes with the geometry of the injector, the air/oil pressures and the fluid properties. For the second application, theoretical and experimental studies (Steimes 2011) showed that the deoiling efficiency of the Pump and Separation System (PASS) is directly related to the droplet distribution in the inlet. At the outlet of the separator, small droplets (< 3 μm) are measured. So, both applications need a good measurement methodology to obtain correct and reliable results. They both need a deep knowledge of the droplet size distribution to predict the performance of each lubrication system. Furthermore, droplet size distribution is one of the main input parameters for theoretical and computational fluid dynamics studies in those applications.

In this paper, droplet size measuring systems are presented, and a comparison between the results obtained with the Sympatec Helos-Vario/KR Laser Diffraction (LD) system and a Particle Dynamics Analysis (PDA) system is presented. The innovative MQC and PASS systems are presented with their respective test benches and working conditions. The measuring method developed to extract the droplets from the film of annular flows is discussed and the working conditions are presented in function of a parameter chosen to characterize the usability of LD methods. Droplet distribution and Sauter Mean Diameter (SMD) measurements are then presented in function of different variables and compared to theoretical studies.

2. Droplet size measuring systems

The objective of particle grading is to measure the size and the statistical distribution of particles flowing in one group. The diversity of the applications matches the multiplicity of the measurement methods. So, several aspects must be taken into consideration to fix the choice of one technique: the characteristics of the particles (size, speed, concentration, state (solid/liquid), etc.) and the environment (temperature, accessibility, ambient pollution, type of working fluid). Electrical and mechanical methods exist, but this paper will focus on particle grading through optical methods, which are more suited to our applications. These optical methods use the light diffusion laws. Two main diffusion patterns can be distinguished based on the size parameter ($\beta = \frac{2 \pi r}{\lambda}$). It is used to classify the diffusion models and relates the radius of the particle r to the wavelength λ of the incident wave. When $\beta \ll 1$, Rayleigh's pattern is used to measure submicron particles. When

$\beta \gg 1$, the Snell-Descartes's laws of reflection, refraction and diffraction can be used. For practical purposes, a third field can be considered when $0.3 < \beta < 30$. This field uses the Lorenz-Mie theory based on the integration of electromagnetism equations inside and outside the particle to allow the complete calculation of the diffusion (for a plane wave and a spherical particle). Optical measurement methods can be classified according to the position of the receptor and the light source (on/off axis). They are presented in Tab. 1 by grading technique and with their limitations. More information on the measuring principle of each technique can be found in Kleitz 1995.

Table 1: Optical particle measurement techniques

Technique	On/off axis	Limits
Particle counting	off	Response curve dependent on calibration. Signal intensity depends on absorption and lightning of the ambient.
Phase Doppler anemometry	off	Lower limit depends on the phase and size of the particle (1 µm). Upper limit is reached when the particle has the size of the laser beam (few millimeters). PDA measures a very small zone of the flow (~1 mm³) and alignment of the receiver with the measurement volume is difficult.
Holography	on	Slow analysis, dependent on the distance of the measuring zone l, low particle concentration limit ($d^2 = \lambda\, l$).
Laser diffraction	on	Lower limit is defined by the optical limit (> 0.1 µm), upper limit by resolution in the center of diffraction figures (> 15 mm).
Shadowscopy	on	Large particles (> 5µm).

The Sympatec LD system includes two lenses to measure droplet sizes between 0.9 – 175 and 9 – 1750 µm. As it is inherent to LD systems, those lenses have different working distances between the detector and the measuring zone (respectively 96 and 566 mm). The detector is connected to a PC for post-processing. This LD system was chosen due to its large particle size spectrum, as it will be used for different applications and for its simplicity (no alignment needed, only a section of the flow is measured) and the test bench accessibility. It uses a Fraunhofer diffraction method, which consists in analyzing a light intensity distribution. Particles with the same size and of any position will give the same diffraction pattern as Fraunhofer diffraction only depends on the diffusion angle and the size coefficient β. It does not depend on the refraction index n_l. The intensity I of the global diffraction figure depends on the particles radius distribution f(r):

$$I = K \int_0^\infty f(r)\, r^4 \left[\frac{J_1(\beta\theta)}{\beta\theta}\right]^2 dr \qquad (1.1)$$

where J_1 is the Bessel function of the first order, K a constant and θ the diffusion angle.

3. Lubrication systems, their test benches and working conditions

3.1 *Minimum quantity cooling lubrication*
Near dry, or Minimum Quantity Cooling Lubrication (MQCL) machining provides significant reduction of the cutting fluid consumption (compared to conventional flood cooling) and an increase in machinability and tool life (compared with completely dry machining). MQCL has been proven to be competitive when the process generates heat that assists reducing friction and cutting forces. Its application is limited to non-ductile materials since dry machining of ductile materials (e.g. some aluminum alloys) results in high adhesive wear (Byrne 2003; Klocke 1997; Khan 2009). MQCL is a cutting fluid delivery method where the fluid, usually a straight biodegradable oil, is delivered to the cutting point in quantities between 10 to 500 ml/h (Wineret 2004; Dhar 2006). Straight oil can be replaced by an emulsion with higher heat capacity due to its water content. The

process is then referred to as MQC. While it remains largely unexplored, it could provide solutions to machining processes with high heat generation (Diakodimitris 2011). The MQCL fluid can be fed either in the form of a succession of droplets or with the assistance of a transporting medium (air or CO_2) as an aerosol spray (Tawakoli 2009; Aoyama 2002). The delivery of the fluid can occur externally, via one or more nozzles directed towards the cutting zone, or internally via built-in channels in the tool, the chuck or the spindle. External supply systems are more suitable in milling, turning and grinding operations (Weinert 2004; Zeilmann 2006). An internal supply system ensures the availability of cutting fluid close to the cutting edge in applications where external supply would be obstructed or inefficient (e.g. drilling holes of large length to diameter ratios). A second distinction could be made as the supply of the lubricant to the nozzles (or to the tool in the case of internal delivery) can be fed via a single channel containing the aerosol mixture, or via two channels in which case the mixing occurs directly ahead of the tool (Weinert 2004).

To test the injectors, an emulsion (Emultec VG: water-soluble coolant and esterified vegetable oil, $n_l = 1.338$) at 5% concentration is used. The test bench operates with pressurized air and is showed on Fig. 1. The oil is fed to the atomizers through a volumetric pump and regulators. The air gets to the system and passes through a filter, a dryer and a pressure regulator before reaching the atomizers. The air flow rate is measured by a mass flowmeter and the oil flow rate by a pressure sensor (the pressure/flowrate characteristic was calibrated before).
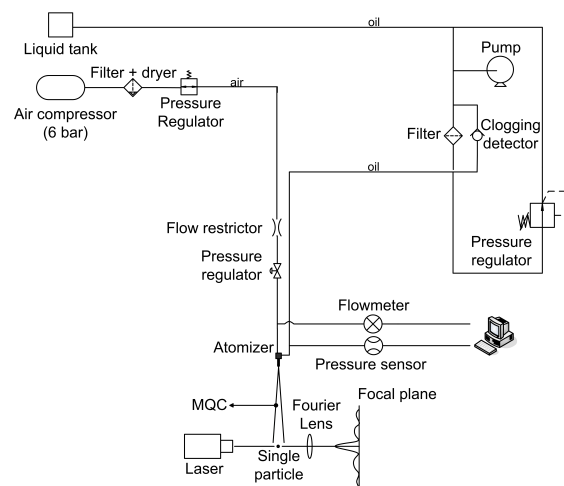

Figure 1: MQC test bench

The airblast injector (from Systems Tecnolub sa.) used for the experiments is detailed in Fig. 2. The liquid orifice d_0 is smaller than 0.5 mm and the gas orifice is defined by d_{ge} (4.25 mm) and d_{gi} (2.75 mm). The airblast injector has been placed at an axial distance of the laser beam so that the jet is fully atomized.

3.2 Pump And Separation System
In aircraft gas turbine engines, the lubrication and cooling of the bearings is performed by oil injection in air sealed chambers, generating a two-phase flow of oil and air. This air is provided by low-pressure compressor bleed air. A vent line collects the sealing air, and brings it to a de-oiler where the oil droplet laden air is cleaned before leaving through the overboard. Scavenge volumetric pumps collect an oil/air mixture from the bearings compartments and the gearboxes. This mixture is de-aerated in a cyclone separator located at the entrance of the oil tank. For several years now, the ATM department is studying a device to separate a gas/liquid flow and simultaneously pressurize the liquid for aeroengine lubrication systems (Gruselle 2011). It will
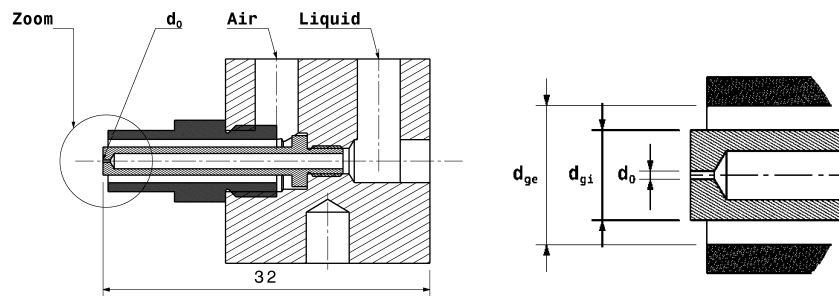
Figure 2: Coaxial airblast plain-jet atomizer configuration (dimension in mm)

insure the de-aeration, de-oiling and pressure function of the scavenge system. They are key parameters for this scavenge part of lubrication systems. The de-oiling efficiency is directly linked to the oil consumption of the engine as the overboard vent represents the only outlet of the scavenge system. This consumption has to be lowered regarding environmental and economical factors, but also regarding the limited in-flight oil quantity. Increasing the efficiency of aeroengines leads to an increase of working temperatures, pressure levels, shaft speeds, ... Combining this with the "more electric" aircraft and engines implies higher thermal loads on the engine bearings and on the oil feeding system. Furthermore, studies are performed to study the influence of a change of the bearing seals (i.e. changing the air flow rate). Therefore, a comprehensive study on the influence of those key parameters on the de-oiling and de-aeration has to be performed. This paper is focused on the influence of those parameters on the droplet distribution at the inlet of the prototype, and on the measurement of the droplet distribution at the outlet. It will be shown that the oil consumption is directly linked to the size and distribution of the oil droplets in the two-phase inlet flow. Those parameters are influenced by oil/air flow rates and flow temperature as well.

The ATM Department owns a certified test bench for aero-engine lubrication systems. It provides a gas/liquid mixture, in varying proportions, to the inlet of the pump and separation prototype. This is performed through mixing chambers that are fed with air from a compressor and hot oil from a tank (Mobile Jet oil II, through a volumetric lubrication pump). The purpose of those chambers is to simulate the air/oil mixture coming from the bearing chambers. The two flow rates are measured by two flowmeters (precision of 1 to 2% of the measure). The inlet pressure is taken as the sump pressure, with calibrated pressure transducers (0.2% full scale precision). Pt100 thermal sensors are used to measure inlet temperatures. Pressure transducers and Pt100 are also used at the air and oil outlets. Data's are collected with a 4-20 mA National Instruments acquisition card and are post-processed with LabView. More information can be found in Gruselle (2011).

### 3.3 Working conditions and flow measurement characteristics

The two applications work with completely different air and oil flow rates. The measure occurs in a 38 mm diameter pipe (PASS) or a free air section (MQC). To characterize the usability of LD systems, a parameter was defined to represent this difference in oil/air ratios and measuring sections ($\phi_{l/g} = \dot{q}_l/\dot{q}_g$). For medium values of $\phi_{l/g}$, tests are performed easily. For very low values, the limits of LD systems are met in droplet size and working distances. For higher $\phi_{l/g}$, measurements are complicated as the amount of droplet increases and lead to multiple scattering. Furthermore, all the oil is not necessarily under a droplet form and may cause measurement perturbation. Range of $\phi_{l/g}$ for both applications is given in Tab. 2.

The 9 – 1750 μm lens was used for the MQC studies as it covers the range of created droplets. The receptor and emitter of the LD system are spaced to avoid droplet deposition on the lens ($\phi_{l/g} = 2\,e^{-4}$). This bench and the LD configuration showed a good usability. For the PASS there are two

Table 2 : Tested conditions for the different applications

	$\dot{q}_{lM}$ (m³/s)	$\dot{q}_{lm}$ (m³/s)	$\dot{q}_{gM}$ (m³/s)	$\dot{q}_{gm}$ (m³/s)	T_l (°C)	$\phi_{l/g}$
MQC	4.10 e⁻⁷	1.67 e⁻⁷	7.50e⁻⁴	3.33 e⁻⁴	20	2.2 e⁻⁴ - 1.7 e⁻³
PASS Inlet	4.17 e⁻⁵	1.77 e⁻⁴	3.33 e⁻²	1.67 e⁻²	20 - 30	1.07 e⁻³ - 1.06 e⁻²
Pass Outlet	4.25 e⁻⁹	1.7 e⁻⁹	5.56 e⁻²	2.22 e⁻²	20 - 30	6.4 e⁻⁸ - 7.6 e⁻⁸

measuring cases: at the inlet or at the outlet of the separator. The two-phase flow pattern in the inlet pipe can be identified using two-phase flow maps (as showed by Fig. 3). With the PASS working conditions, it is an annular flow (a gas core laden with oil droplets surrounded by a liquid ring as showed on Fig. 4). Parameters usually characterizing this type of flow are the amount of entrained liquid as droplet (by the gas) and the droplet size distribution.
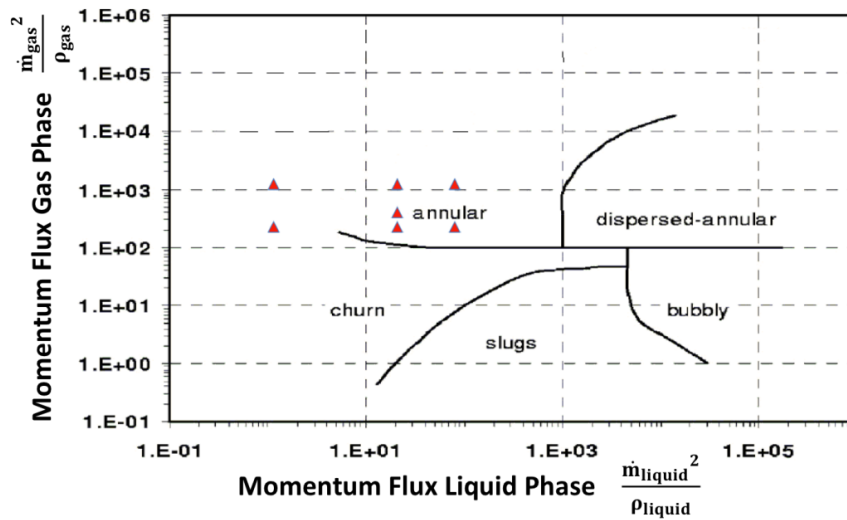
Figure 3: Working conditions in two-phase flow regimes (originally prepared by Willenborg et al (2008))

The liquid film of the annular flow needs to be removed in order to measure the droplet distribution. This is usually done by a porous medium located in the pipe before the measuring zone. Nevertheless, oil/air flow rates and pipe diameters used in other annular flow studies differ from ours (according to Tab. 3, this study has the highest liquid mass flux and lowest gas mass flux). Experimental tests showed that it is difficult to totally remove the liquid film at high liquid flow rates. So, instead of extracting the film, a part of the droplet flow is extracted from the pipe, before the measuring zone, has shown on Fig. 4.

Table 3: Gas and liquid mass flux of different studies (data taken from Azzopardi 1991)

	Gas mass flux (kg/m² s)	Liquids mass flux (kg/m² s)	Pipe diameter (mm)
Current study	18 - 42	25 -306	38
Azzopardi et al. (1980)	43 - 115	16 - 160	32
Azzopardi et al. (1983)	43 - 115	7.5 - 25	125
Gibbons (1985)	55 - 80	30 - 80	32
Teixeira et al. (1988)	43 - 91	16 - 125	125
Zaidi et al. (1998)	30	33 - 101	38

The 9 – 1750 μm lens is used. Some complications appeared when the oil flow increases, as explained before for $\phi_{l/g} < 5.31\ e^{-3}$. Different sizes of the extraction pipe were tested and no relevant difference appeared).

At the outlet of the PASS, the air flow is loaded with few particles, so the 0.9 – 175 μm lens can be used without lens pollution. However, experiments showed that the particle diameters are very low and the LD system does not allow to see clear differences in the results (for a $\phi_{l/g} < 7.6\,e^{-8}$).
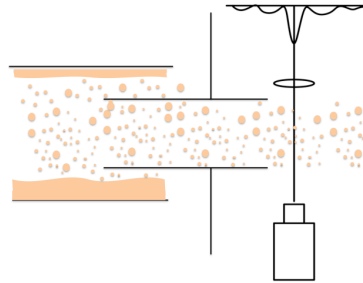

Figure 4: Droplet extracting system for annular flows

4. Experimental results and theoretical comparison

4.1 LD - PDA comparison on an injector

To validate the laser diffraction results obtained with the Sympatec system, a comparison with another laser-based technique was performed. The injector tested in this paper (Fig. 2) has been studied with a single velocity component phase Doppler system from Dantec Dynamics. Figure 5 shows the droplet density distribution measured with the two techniques for air and oil flow rates of respectively 31 l/min and 10 ml/min. Figure 5 clearly shows a good agreement between the two techniques. The LD system shows a density distribution slighlty shifted towards small droplets. Zaidi et al. (2010) performed the same comparison on annular flows and had the same conclusions, what confirms the results found in this paper. This comparison allows to be confident in the results of LD measurements for average droplet sizes.
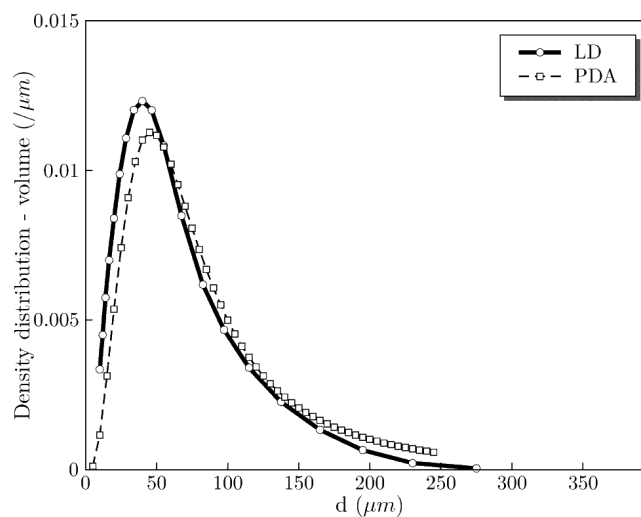

Figure 5: Comparison between LD and PDA measurements

4.2 MQC: experimental results and theoretical comparison

The results obtained with the LD systems are from 30 s tests (mean values of 3 measurements). Lorenzetto (1977) investigated atomization processes in plain-jet air blast nozzles and obtained the following empirical equation for the SMD (d_{32}):

$$d_{32} = 0.95 \left[\frac{(\sigma_l \dot{m}_l)^{0.33}}{\rho_l^{0.37} \rho_g^{0.30} u_r} \right] (1 + \frac{\dot{m}_l}{\dot{m}_g})^{1.70} + 0.13 (\frac{\mu_l^2 d_0}{\sigma_l \rho_l})^{0.5} (1 + \frac{\dot{m}_l}{\dot{m}_g})^{1.70} \qquad (4.1)$$

An increase of the air flow increases the atomization of oil (reducing the SMD). An increase of the oil flow increases the SMD. Figure 6 shows the measured SMD and the results given by Eqn. 4.1. It clearly shows a good agreement between theory and experiments but shows a divergence for low air flow rates. Actually, Eqn. 4.1 of Lorenzetto (1977) is valid for air velocities of 60 m/s and higher (i.e. air flow rate of 30 l/min, Tab. 4). The value of $\phi_{l/g} = 2e^{-4}$ showed a good usability.
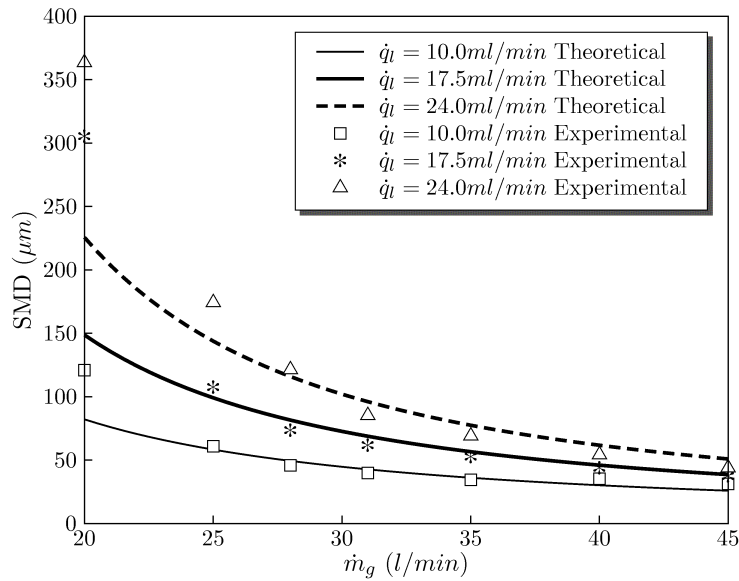

Figure 6: Comparison between experiments and theory for the MQC injector

Table 4: Test conditions employed in experimental studies.

		σ_l	ρ_l	μ_l	p_g	T_g	u_g	Air/liquid
		(10^3 kg/s^2)	(kg/m^3)	(10^3 kg/ms)	(10^{-5} Pa)	(K)	(m/s)	mass ratio
Lorenzetto et al. (1977)	Water, kerosene, special solutions	26-76	794-2180	1 -76	1.0	295	60-180	1-16
This study	Emulsion	73	1006.5	1.0	1.0	293	40.4-91.0	1-5.4

4.3 Pass experimental results, theoretical comparison and limits of the LD system

The results obtained with the LD systems are from 30 s tests (mean values of up to 5 measurements for the inlet flow and 20 measurements for the outlet flow).

Inlet flow

Predicting the droplet distribution of the annular flow in the inlet pipe is necessary to model the separation efficiency of the PASS (Gruselle 2011, Steimes 2011). Annular flows have been widely studied in the literature (Azzopardi 1997) and semi-empirical correlations have been developed to predict the droplet distribution and the entrained liquid droplet mass flow. A correlation for the SMD of annular pipe flows is given by Simmons (2001) as Eqn. 4.2.

$$d_{32} = \left(\frac{\sigma_l}{\rho_{lg}}\right)^{0.5} \left[A \left(\frac{\rho_g (u_g^s)^2 (\sigma_l/\rho_{lg})^{0.5}}{\sigma_l}\right) + B \left(e \frac{u_l^s}{u_g^s}\right) \right] \qquad (4.2)$$

A and B are parameters determined experimentally (usually, $A = 0.33$ and $B = 3.5$ or 18.6). Cioncolini et al. (2010) proposed a correlation to estimate the entrainment rate e:

$$e = (1 + 13.18 \, We_c^{-0.655})^{-10.77} \qquad (4.3)$$

where We_c is a Weber number calculated with an iterative procedure to take the thickness of the liquid film into account. Droplet distribution is described by the Rosin-Rammler continuous distribution function in Eqn. 4.3 but other distributions can also be used (Lefebvre 1989). The spread parameter n is chosen to fit the experimental data.

$$F_m(d) = 1 - \exp\left(-\frac{d}{d_{32}\Gamma(1-1/n)}\right)^n \qquad (4.4)$$

The dependence of d_{32} with the liquid flow is not unanimous, but an increase of the air flow shifts the droplet distribution curve to the left as more oil is entrained and atomized. Figure 7 shows this for an oil flow rate of 160 l/h. One can see that the curves shift to lower droplets sizes when the air flow rate increases. The quantity of droplets (entrainment) increases as the measured optical concentration goes from 2 to 5%. Tests at higher oil flow rates showed the same trend (optical concentration even going from 15 to 50% for $\dot{q}_l= 640$ l/h). Those results helped to understand the decrease in the PASS separation efficiency with high air and oil flow rates (i.e more small droplets which are difficult to separe). As explained before, it was not possible to reach higher air or oil flow rates ($\phi_{l/g} < 5.31e^{-3}$). The LD system did not always measure droplets with $d < 13 \, \mu m$ when the optical concentration increased. This may lead to an overestimation of the SMD.

Fig. 8 shows the comparison between experimental and theoretical results. The value of B that matches our test results is 18.6. The SMD was measured for 3 oil flow rates (160, 320 and 640 l/h) and 4 air flow rates (60, 80, 100 and 120 m³/h). The correlation in Eqn. 4.2 has the best prediction performances above 35 m/s (i.e. 140 m³/h in the test bench) and one can see that the correlations is accurate for the largest air flow rates (> 100 m³/h).
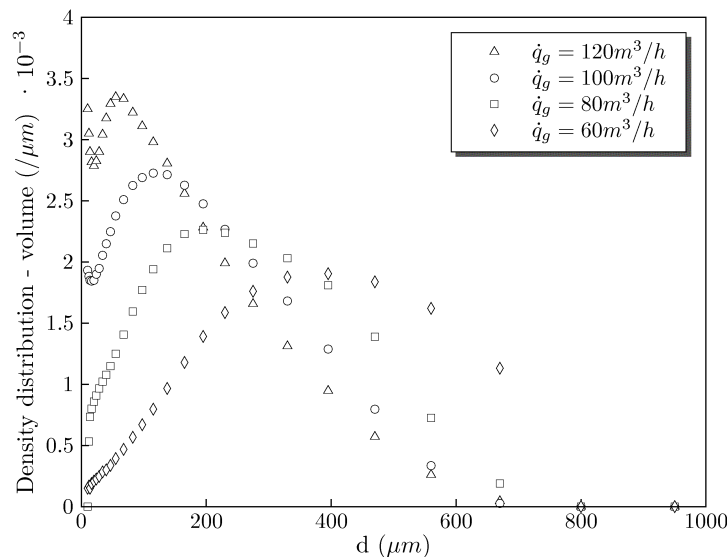

Figure 7: Droplet density distribution for an annular flow with $\dot{q}_l = 160$ l/h and different air flow rates
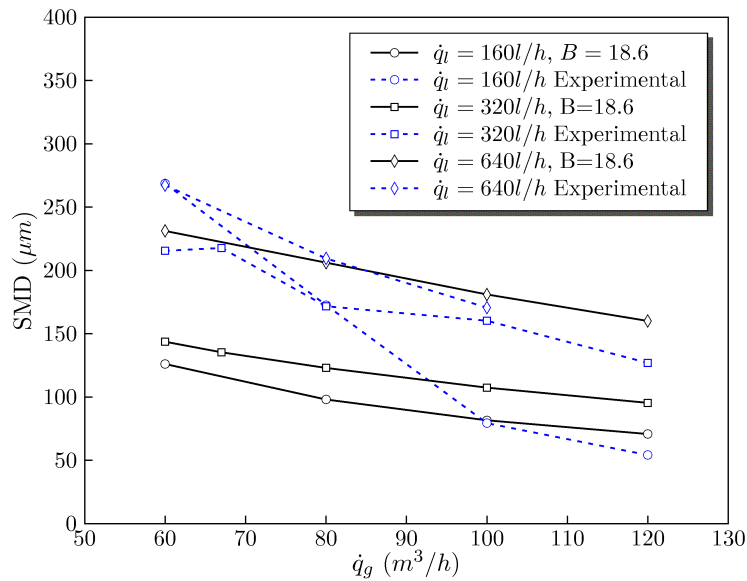
Figure 8: Theoretical and experimental SMD

It is possible to find the droplet distribution by using the Rosin-Rammler distribution and adjusting the spread parameter. This is illustrated in Fig. 9 (when the theoretical and experimental SMD matches), when $n = 1.75$. This value of n is coherent with the literature and was found to be recurrent to fit correctly the results at 620 l/h. Experimental and theoretical curves are close, especially in the small droplet diameters that are of importance for the PASS.
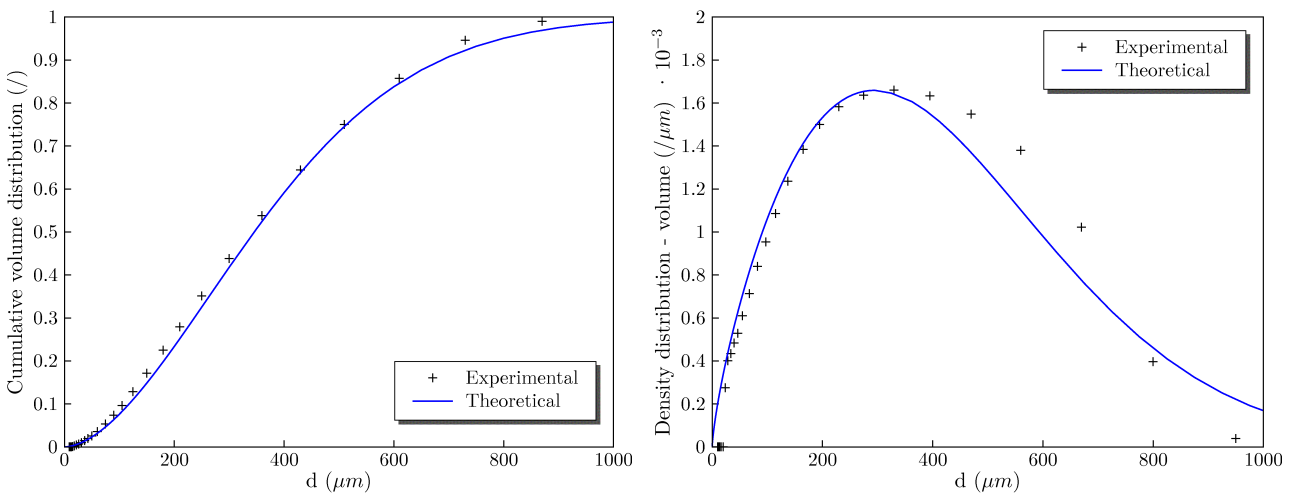

Figure 9: Cumulative and density droplet distribution for $\dot{q}_g$ = 100 m³/h and $\dot{q}_l$ = 620 l/h

Outlet flow

Measurements performed after the separation of the annular inlet flow by the PASS are showed in Fig. 10 (for different oil/air flow rates). One can see that no clear difference is observed between the tests and that the droplets have a small diameter (< 3 μm). This result was expected as Willenborg et al. (2008) tested the same kind of separator and obtained SMD measurements around 0.5 μm while we have a range between 0.9 and 1.3 μm. When measuring the outlet flow, the limits of the lens are quickly reached as droplets smaller than 0.9 μm are not measured. Using a smaller focal distance lens could improve this but the working limit distance would be reached. In this case, there is a 20 mm distance between the lens and the 38 mm pipe and reducing this distance leads to lens

pollution. Furthermore, building a measuring cell in such small distance is very difficult. So, the lower limit of laser diffraction measuring method is reached (when $\phi_{l/g} = 7.6\,e^{-8}$). Willenborg also observed this and developed an in-house measuring system for small droplet diameters.
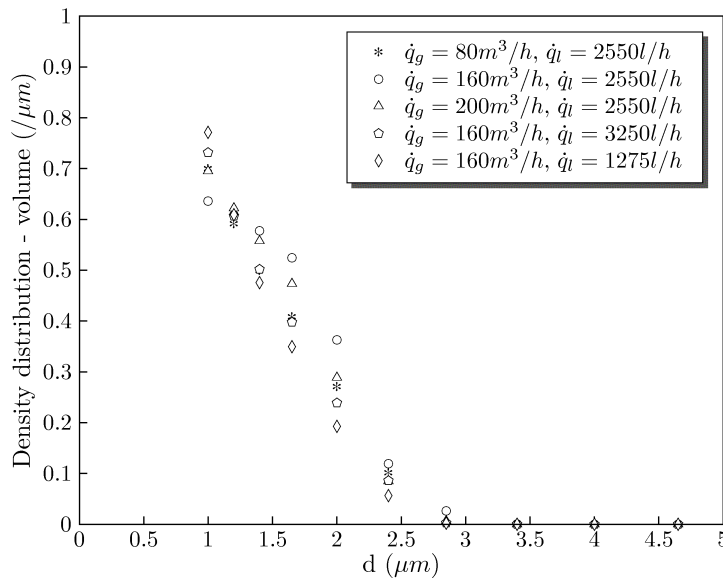

Figure 10: Comparison of the droplet distribution at the outlet of the PASS

6. Conclusions

Nowadays, laser diffraction measuring methods become more and more often used. This paper presents two innovative lubrication solutions, the minimum quantity cooling for machining purposes and a pump and separation solution for aero-engine lubrication systems, where this laser method was used to measure droplet distributions. The lubrication systems and test benches are presented and the importance of predicting a correct droplet distribution is explained.

A comparison between LD and PDA measurements performed on an injector, are presented and show a good agreement. The PDA shifts the droplet distribution towards the larger droplets. Results of both systems (spray and annular flows) are compared to semi-empirical models and in the boundaries of validity of these models, the prediction of droplet distribution is successfully compared to the experimental results. Nevertheless, the difference observed out of those boundaries should lead to the definition of new semi-empirical models fitted on the experimental results.

A parameter was introduced to characterize usability of LD systems. It compares the amount of liquid to measure on the measuring surface and on the gas flow. A lower limit of this parameter showed that the tests were reaching the limits of LD systems for small droplets as the limit in working distance was reached. An upper limit is defined by high liquid and gas mass flux where the amount of droplet lead to multiple scattering and hiding small droplets. Spray applications on the other hand, represented by a mean value of this parameter showed easy and repeatable results. Some other applications should be tested in order to confirm this parameter as an interpretation of the usability of LD systems.

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