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CORRELATION LAW FOR SMD IN HIGH VISCOUS SPRAYS

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ABSTRACT

Spray characterization, i. e. a velocity map of the liquid and gaseous phases and the sizing of the liquid droplet, remains of a great importance in different industrial applications such as in the automotive or pharmaceutical industries. Correlations capable to faster this characterization already exist. They allow the evaluation of the droplet Sauter Mean Diameter in a precise location of the spray using non-dimensional numbers involving physical and chemical properties of the liquid and the spray operative conditions. This paper concerns the possibility to include in the correlative laws also the effect of the liquid viscosity through the introduction of the Ohnesorge number (Oh). In order to achieve this goal an extensively experimental campaign is performed, by means of a Phase Doppler Interferometer, for size and velocity measurements in a full cone spray. Parameters as the hydraulic diameter of the nozzle, the operatingpressure and the liquid viscosity are varied in order to cover large range of Weber and Ohnesorge numbers.

INTRODUCTION

Sprays are encountered in many industrial fields such as in automotive or chemical processes. In agronomy, sprays are encountered for the …. In the framework of security, sprays are used to confine accidental release of toxic gazes or to protect storage tanks from thermal radiation of flames.

In the aforementioned applications the nozzle size and configuration vary in a broad range. Spray shape go from flat to cone, spray angle for few to 360 degrees and droplet size from about ten of microns to millimeters. The choice of the spray and of operating condition for a particular application is of a great importance for its good utilization. The interest in studying sprays of high viscous liquids is related to different branches of industries as the coating industry where viscous paints are used or the alimentary one where vegetal oils and syrup are employed. The complexity of spray formation is unfortunately incremented when non-Newtonian fluids are employed since their relation between shear stress and shear rate is not linear anymore [1].

The final scope of this paper is to introduce an empirical law to predict the Sauter Mean Diameter in a specific point of a spray using properties of the liquid and of the spray itself. Similar studies have already been conducted allowing the establishment of correlation for the SMD as function of the Reynolds number (Re) and the Weber number (We). In this work attention is paid on the behavior of the SMD as function of the liquid viscosity and surface tension with the use of the Ohnesorge number (Oh) which relates the viscous and surface tension forces results to be independent from the flow characteristics.

This paper is divided in five sections. The first section yields an introduction to the problematic of high viscous sprays. The second section is devoted to the description of the experiment campaign and of the experimental methodology. The Laser Doppler interferometer technique is briefly introduced. The third section is devoted to the presentation of the results. Their exploitation and the comparison with other correlations found in bibliography with a critical review on previous works on high viscous spray characterization is also described. Finally the conclusions summarizing the important achievements of the study and future plans focusing on research for non-newtonian fluids are given.

EXPERIMENTS

The nozzles used during the experimental campaign are of Lechler swirl type. Their characteristics are listed in Table 1 and a picture of them is proposed in Figure 1.

Table 1 Swirl Nozzles characteristics

Lechler code	D_h(mm)	Spray angle [deg.]	Flow rate[l/min] at ΔP 300 K Pa
460.403	1.07	45	1.18
460.603	1.91	45	3.70
460.683	2.37	45	5.88

Figure 1 Picture of the nozzles used during the measurement campaign.

Different aqueous-glycerin solutions are used during the tests.

The tests allow covering the following ranges for Weber and Ohnesorge numbers:

1. We $\in [3 \div 274]$,
2. Oh $\in [8.7 \cdot 10^{-5} \div 5.8 \cdot 10^{-3}]$.

The characteristics of the solution used, namely their viscosity and their surface tension at ambient temperature are listed in Table 2, while the tests performed during the measurement campaign are listed in

Table 3 . These tests are performed at about 15 cm from the nozzles exit.

Table 2 Physical properties of the liquid used at ambient temperature (T=20 °).

G/W % weight	μ [mPa s]	ρ [kg m^{-3}]
81	64.16	1209.2
74	30.52	1190.6
51	6.22	1126.7
1	1.02	996.2

Table 3 Tests performed during the measurement campaign.

G/W % weight	P [kPa]		
	D_h [mm]		
	2.4	1.9	1.08
81	530 ÷1500	1470	1550
74	260 ÷1450	170 ÷1500	1000 ÷1880
51	220 ÷1550	200 ÷1480	185 ÷1410
1	104 ÷1560	120 ÷1600	110 ÷1540

Experiments are performed by means of a Phase Doppler Interferometer (PDI) from Artium Company. The Phase Doppler interferometer is a non-intrusive laser-based technique for the measurement of size and velocity of liquid droplets. It is not the purpose of this communication to explain in details the PDI technique, only the principle is recalled. More detailed information can be found in [2].

In PDI technique a laser beam is divided in two parts of equal intensity which converge in one single location where interference fringes are created. A droplet passing through these fringes scatters light at a frequency related to its velocity. This scattered light is collected by three photomultipliers positioned with a particular angle with respect to the laser light.

The phase shift presents between the signals on the three photomultipliers is related to the droplet size. A picture of the PDI set- up is shown in Figure 2.

RESULTS AND CORRELATION LAW

The Sauter Mean Diameters measured during the test campaign are compared with the ones obtained using a correlation for swirl nozzle proposed by Wang and Lefebvre [3],[4]. Their model is derived from basic consideration of the hydrodynamic processes that govern the atomisation process in pressurised-swirl nozzles. This atomisation results from two mechanisms.

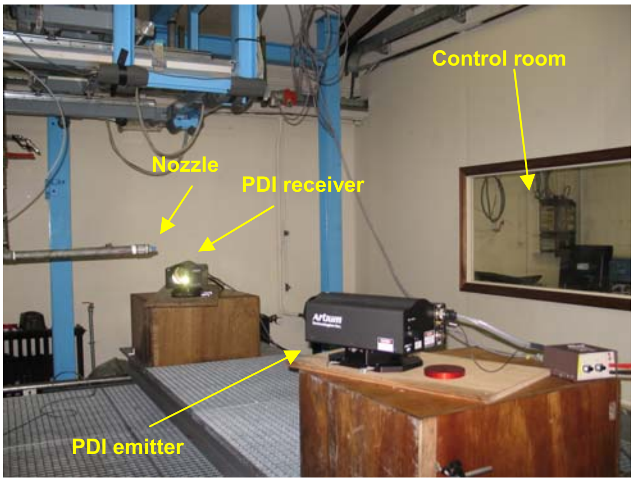

Figure 2 Picture of the Phase Doppler Interferometry set-up.

The first mechanismstage represents the generation of surface instabilities caused by the combined effects of hydrodynamic and aerodynamic forces. The second mechanism is the conversion of surface protuberances into ligaments and the drops. This simplification leads to a two member formulation :

$$\mathrm{SMD} = \mathrm{SMD}_1 + \mathrm{SMD}_2 \qquad [3]$$

The first member magnitude depends partly on the Reynolds number, a measure of the disruptive forces within the liquid sheet and on the Weber number which governs the development of ripples on the liquid surface.

Based on experimental data, the following relationship was established:

$$\frac{\mathrm{SMD}_1}{t_s} \propto \left(\mathrm{Re} \times \sqrt{\mathrm{We}}\right)^{-x} \qquad [4]$$

where t_s is the initial thickness of the liquid sheet, Re is the Reynolds Number and We is the Weber number. These last two non-dimensional numbers are defined as follows:

$$\mathrm{We} = \frac{\rho_L v_o^2 D_o}{\sigma} = 4\frac{\rho_L Q^2}{\sigma A_o P_m}$$

$$\mathrm{Re} = \frac{\rho_L v_o D_o}{\nu_L} = 4\frac{\rho_L Q}{\nu_L P_m} \qquad [5]$$

where ρ_L is the liquid density, v_o is the velocity of the liquid jet at the exit of the nozzle, Q is the liquid flow rate, σ is the liquid surface tension, A_o is the initial liquid jet cross section, P_m is the initial wetting perimeter and ν_L is the liquid kinematic surface viscosity.

The second member, SMD2 represents the final stage of the atomisation process in which the high relative velocity induced at the liquid/air interface causes the surface protuberances created at the first stage to become detached and break down into ligaments and then drops. This disintegration is governed by surface tension forces and Reynolds number is no longer relevant, what leads to the following relationship:

$$\frac{\mathrm{SMD}_2}{t_s} \propto \mathrm{We}^{-y} \qquad [5]$$

Values, suggested for x and y, are respectively 0.5 a 0.25. It results then that in the Wang model:

$$\frac{SMD}{t_s} \propto \left(Re^{-0.5}+1\right)\cdot We^{-0.25} \qquad [$$

The final expression of the SMD is then

$$SMD = A\left(\frac{\sigma\mu^2}{\rho_A \Delta P_L^2}\right)^{0.25}\left(t\cos\theta\right)^{0.25} + \qquad [$$

$$B\left(\frac{\sigma\rho_L}{\rho_A \Delta P_L}\right)^{0.25}\left(t\cos\theta\right)^{0.75}$$

where θ is defined as half of the spray opening angle. and B are respectively equal to 4.52 and 0.39. A comparis between the experimental SMD and the one computed wi Eq. [7] is shown in Figure 3.

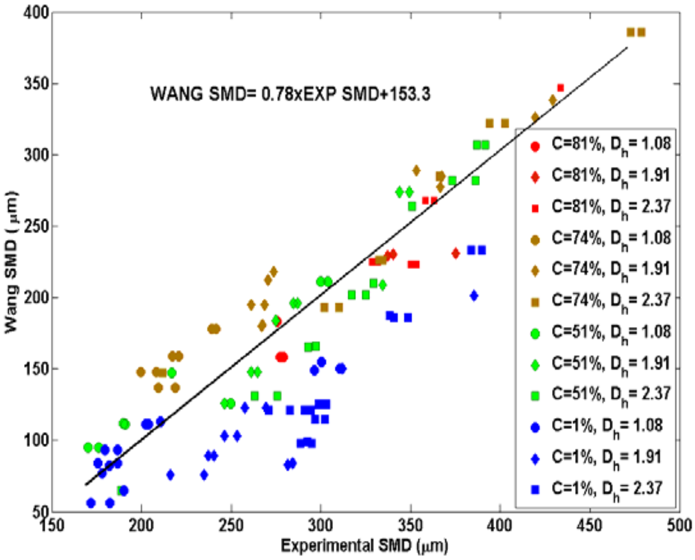

Figure 3 Comparison between the Sauter Mean Diameter computed with Wang formula and the experimental one obtained during the present measurement campaign.

One observes that the Wang formulation does not fit properly the experimental data. In particular the effect of the liquid viscosity is still present (see points corresponding to C=1%).

Figure 4 shows the dependence of the experimental SMD on the liquid pressure is shown on. The SMD increases as the Glycerin concentration and then the solution viscosity augment. The pressure effect can be modeled by:

$$SMD \propto P^{-\delta} \qquad [8]$$

where the exponent δ increases with the solution viscosity.

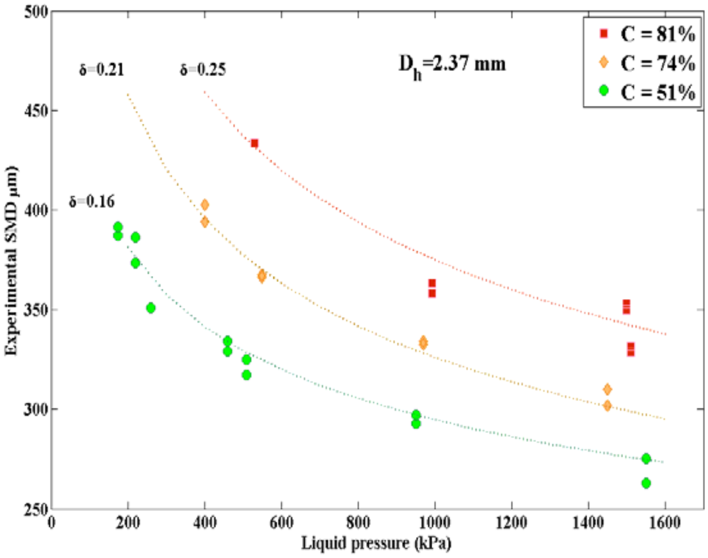

Figure 4 Evolution of the SMD as function of the liquid pressure for three different concentration of Glycerin in water.

The dependence of the exponent delta as function of the liquid viscosity is represented in Figure 5

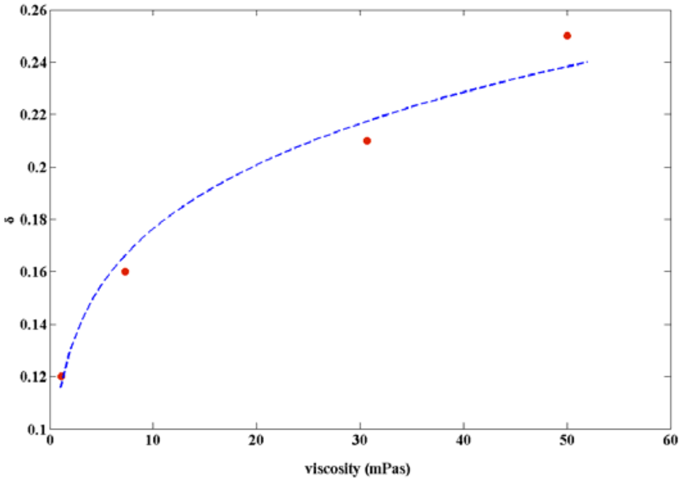

Figure 5 Dependence of the delta exponent as function f the liquid viscosity.

In the same way the dependence of the experimental SMD on the Weber number follows also a power law of the type :

$$\frac{SMD}{D_h} \propto We^{-\beta} \qquad [9]$$

where β is extrapolated from the experimental data and is equal to 0.23, which is in a good agreement with the value present in Eq. 6.

As stated before, the purpose of this paper is to establish a simple correlation law for the SMD of high viscous liquids. This correlation law contains the non-dimensional Weber and Ohnesorge number.

The last one being defined as:

$$Oh = \frac{\nu_L}{\sqrt{\rho_L \sigma D_h}} \qquad [10]$$

and it depends only on the physical characteristics of the liquid and on the hydraulic nozzle diameter.

The correlation law proposed in this work is expressed by Eq. 11

$$\frac{\mathrm{SMD}_{\mathrm{corr}}}{\mathrm{D}_{\mathrm{h}}} = \frac{\mathrm{A}}{\mathrm{D}_{\mathrm{h}}} + \mathrm{B}\cdot\mathrm{Oh}^{\alpha}\cdot\mathrm{We}^{-\beta} \qquad [11]$$

where numerical values of the constants Eq. 11 are listed in Table 4

Table 4 Values of the constants of Eq. 8

Constant	Value
A	$7.6\mathrm{x}10^{-4}$ [m]
B	1.095
α	0.2
β	0.23

A comparison between the experimental SMD and the one obtained using Eq. 11 is shown in Figure 6.

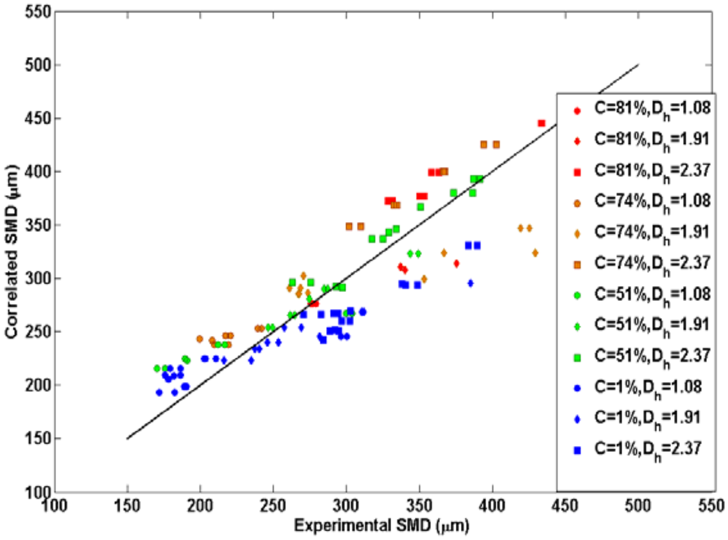

Figure 6 Comparison between the Sauter Mean Diameter computed with Eq. 11 and the experimental one.

CONCLUSIONS

This paper presents first results about spray droplet characterization for high viscous liquid. The droplet size measured during the experimental campaign has been compared with a previous theoretical model. This comparison shows that the experimental SMD has a linear dependence on the one obtained with the theoretical model. Moreover the experimental points related to the lowest viscosities do not fit well the theory.

The purpose of this paper is to propose a different correlation law for the prediction of the SMD for high viscous fluids. This correlation is expressed as function of the Weber and the Ohnesorge number. The correlation law expressed in Eq. 11 fits well the experimental points even if it does not take into account some of the spray characteristics as the opening angle.

NOMENCLATURE

Symbol	Quantity	SI Unit
D_h	Hydraulic diameter	m
D_o	Nozzle diameter exit	m
A_o	Nozzle surface	m^2
P_m	Wetting parameter	m
v_o	Nozzle exit velocity	m/s
SMD	Sauter Mean Diameter	
We	Weber number	
Re	Reynolds number	
Oh	Ohnesorge number	
Q	Flow rate	m^3/s
ρ	Density	Kg/m^3
ν	Kinematic viscosity	Pa/s
σ	Surface tension	N/m
C	Concentration	
t_s	Film thickness	m
x	Coefficient	
y	Coefficient	

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