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EFFECT OF NOZZLE CONSTRUCTION ON THE CHARACTERISTICS OF TWIN-FLUID ATOMIZATION

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ABSTRACT
This paper presents the results of an experimental study of twin-fluid plain-jet air-assist atomizers with internal mixing with the application of the digital microphotography method. The photographs were analyzed using Image Pro-Plus by Media Cybernetics. The nozzles had internal outlet diameter for liquid flow from 1.06 to 3.00 mm and external outlet diameter for mixture flow from 2 to 6.00 mm. The studies were performed at flow rates of liquid phase changed from 0.0014 to 0.011 [dm^3/s] and of gas phase changed from 0.28 to 1.4 [dm^3/s], respectively. The analysis of the photos of water atomization process showed that the droplet sizes are dependent on: gas and liquid flow rates and construction of nozzle. The experimental results showed that the changes in geometries of a nozzle lead to the significant changes in the spray characteristics. The results of analysis are presented by the relationships of *SMD* as a function of gas to liquid mass ratio *GLR*. Sauter mean diameter for all investigated geometries is decreasing with increase of *GLR* value. It can be seen that *GLR* is a key parameter in determining the quality of atomization. The investigations have shown that *SMD* is decreasing with increase of liquid and mixture outlets diameters. It is evident that the atomizer geometry is the key parameter influencing the liquid atomization.

INTRODUCTION

The atomization of emulsions is wide-spread process in many branches of industry, for instance, in power engineering and combustion engines, in engineering industry and in agriculture. The cooling agent for machine elements, fuel oil, pesticides and milk can be emulsions. In the food industry, oils are used to carry oil-soluble colours, flavours and nutrients that are coated onto the outside of the food. However, many colours, flavours and nutrients are water-soluble, which requires water to be the carrier. Emulsions, which carry both oil and water-soluble additives to the food at the same time, are also commonly sprayed. The studies of emulsions atomization were also directed to improve the combustion performances of emulsions as fuels in furnaces for local power generation [1].

The measuring technique was described by Orzechowski and Prywer [2] and Lefebvere [3]. Measurements of droplet size distributions are routinely made by use of optical techniques. The prediction of droplet size distributions is accomplished through empirical correlations accounting for liquid properties, atomizer design and fluid flows [3].

A typical spray includes a wide range of droplet sizes. Some knowledge of the droplet size distribution is helpful in evaluating process applications in sprays, especially in calculations of heat or mass transfer between the dispersed liquid and the surrounding gas. The Sauter Mean Diameter (*SMD*) is often of use in applications where the active surface or surface area is important, e.g. atomization, catalysis or combustion. The *SMD* is calculated as the ratio:

$$SMD = \frac{\sum_i n_i d_i^3}{\sum_i n_i d_i^2} \tag{1}$$

Many different correlations for *SMD* have been presented in literature. The correlation proposed by Nukiyama and Tanasawa [4] is the more often in use. The investigation of atomization process in a plain-jet atomizer resulted in the empirical equation for the *SMD*:

$$SMD = \frac{0.585}{u_R}\left(\frac{\sigma}{\rho_L}\right)^{0.5} + 53\left(\frac{\mu_L^2}{\sigma\rho_L}\right)^{0.25}\left(\frac{\dot{V}_L}{\dot{V}_G}\right)^{1.5} \tag{2}$$

This equation was obtained at diameters of water outlet from 0.2 to 1.0 mm and nozzle outlet diameters from 2 to 5 mm. The equation applies to a range of air velocities from 60 to 340 m/s and values of gas to liquid mass ratio (*GLR*) from 1 to 14. Hereby *GLR* is defined as follows:

$$GLR = \frac{\dot{m}_G}{\dot{m}_L} \tag{3}$$

The correlation does not take into account diameters of atomizer, density and viscosity of gas.

Rizkalla and Lefebvre [5] investigated atomization process in plain-jet air-blast nozzles and obtained the following empirical equation for the *SMD*:

$$SMD = 0.95\frac{(\sigma\dot{m}_L)^{0.33}}{u_R\rho_L^{0.37}\rho_G^{0.30}}\left(1+\frac{1}{GLR}\right)^{1.70} + \\ +0.13\left(\frac{\mu_L^2 d_{out}}{\sigma\rho_L}\right)^{0.5}\left(1+\frac{1}{GLR}\right)^{1.70} \quad (4)$$

From studies carried out on the atomization of water, with air as the atomizing fluid, Sakai *et al*. [6] derived the following experimental correlation for *SMD*:

$$SMD = 14\cdot 10^{-6}\, d_{out}^{0.75}\left(\frac{\dot{m}_L}{\dot{m}_G}\right)^{0.75} \quad (5)$$

That equation applies to a range of liquid flow rates from 0.008 to 0.028 kg/s and values of gas to liquid mass ratio from 0.01 to 0.2.

Rizk and Lefebvre [7] have examined the effects of air and liquid properties and atomizer geometries on *SMD*. Tests were conducted using two geometrically similar atomizers having liquid orifice diameters of 0.55 and 0.75 mm. The obtained results have shown that the increases in air pressure, air velocity, and *GLR* all tend to lower the value of *SMD*. An empirical equation for *SMD* was derived as follows:

$$\frac{SMD}{d_{out}} = 0.49\left(\frac{\sigma}{\rho_G u_R^2 d_{out}}\right)^{0.4}\left(1+\frac{1}{GLR}\right)^{0.4} + \\ +0.15\left(\frac{\mu_L^2}{\sigma\rho_L d_{out}}\right)^{0.5}\left(1+\frac{1}{GLR}\right) \quad (6)$$

Antkowiak and Heim [8] have investigated atomization process in pneumatic atomizer for dust granulation and obtained the following equation:

$$SMD = 1.06\cdot 10^5\, u_G^{-3.0}\left(\frac{p_{out}}{p_G}\right)^{-4.1}\cdot \dot{m}_L^{0.83} \quad (7)$$

where p_{out} is the pressure of surrounding gas.

Spray nozzles have many important applications and have been the subjects of considerable researches [9-11]. Pneumatic nozzles are operated with comparatively low gas pressures and relatively high efficiencies. A wide variety of designs of this type have been produced for use in industrial gas turbines and oil-fired furnaces. Typical applications are: spray-drying, humidification and evaporative cooling, coating, moistening and greenhouse applications [12]. Several different atomizer designs have been described in the literature [2,3,13].

In the present paper the results of experimental observations on emulsions atomization process in pneumatic nozzles using the digital microphotography method have been presented. The main parameters which have been selected in the experimental characterization of nozzles are the *SMD* and gas to liquid mass flow ratio. The experimental facility, nozzle geometry, measurement method and instruments are introduced.

EXPERIMENTAL APPARATUS

The main elements of the test installation were nozzle, reservoir, pump, measurement units of gas and liquid flows, computer and digital camera with lamps. The nozzles had internal outlet diameter for liquid flow from 1.06 to 3.00 mm and external outlet diameter for mixture flow from 2 to 6.00 mm (Table 1). The investigated emulsion was injected vertically downstream through an atomizer into the room temperature and atmospheric pressure environment. Used oil was a mineral oil 20-90 delivered by Institute of Petroleum Processing of Cracow. The emulsions had the mineral oil volume fraction in range from 0.2 to 0.8. The characteristics of emulsions used are presented in Table 2. The photographs with 3888 by 2592 pixels were obtained using a Canon EOS 1D Mark III camera and an automatic flash that allowed exposure times of 1/8000 s. The photographs were analyzed using Image Pro-Plus delivered by Media Cybernetics which provides in-depth and precise measurement analysis of the parameters of spray characteristics: the spray angle, the spray droplet spectrum produced by a nozzle and *SMD*. The studies were performed at flow rates of liquid phase changed from 0.0014 to 0.011 [dm^3/s] and of gas phase changed from 0.28 to 1.4 [dm^3/s], respectively. It corresponded to *GLR* values from 0.028 to 0.92.

Table 1. Geometry of investigated nozzles

Geometry denotation	Diameter of liquid outlet d_{in} [mm]	Diameter of nozzle outlet d_{out} [mm]
A	1.06	2
B	1.35	3
C	1.65	4
D	2.0	5
E	2.5	6
F	3.0	

Table 2. Characteristics of the emulsions studied

Oil	Φ_{oil} [m^3/m^3]	Denotation	μ_L [Pa·s]	ρ_L [kg/m^3]
20-30	0.2	20-30 0.2	$1.92\cdot10^{-3}$	973
	0.4	20-30 0.4	$3.70\cdot10^{-3}$	946
	0.6	20-30 0.6	$7.13\cdot10^{-3}$	919
	0.8	20-30 0.8	$13.7\cdot10^{-3}$	892
	pure oil	20-30	$26.4\cdot10^{-3}$	866
20-50	0.2	20-50 0.2	$2.12\cdot10^{-3}$	973
	0.4	20-50 0.4	$4.50\cdot10^{-3}$	946
	0.6	20-50 0.6	$9.53\cdot10^{-3}$	920
	0.8	20-50 0.8	$20.2\cdot10^{-3}$	893
	pure oil	20-50	$42.8\cdot10^{-3}$	866
20-70	0.2	20-70 0.2	$2.27\cdot10^{-3}$	973
	0.4	20-70 0.4	$5.14\cdot10^{-3}$	946
	0.6	20-70 0.6	$11.7\cdot10^{-3}$	919
	0.8	20-70 0.8	$26.4\cdot10^{-3}$	892
	pure oil	20-70	$59.9\cdot10^{-3}$	865
20-90	0.2	20-90 0.2	$2.39\cdot10^{-3}$	974
	0.4	20-90 0.4	$5.70\cdot10^{-3}$	948
	0.6	20-90 0.6	$13.6\cdot10^{-3}$	921
	0.8	20-90 0.8	$32.5\cdot10^{-3}$	895
	pure oil	20-90	$77.7\cdot10^{-3}$	869

RESULTS AND DISCUSSION

The exemplary dependence of *SMD* as a function of *GLR* for water atomization is shown in Figure 1. It has been shown that nozzle outlet diameter has effect on produced droplets. Exemplary dependence of *SMD* as a function of *GLR* for 20-70 0.4 emulsion atomization is shown in Figure 2. The comparison of plots presented in Figures 1 and 2 shows that droplets formed during the emulsions atomization have different sizes in comparison with droplets sizes for water atomization. In the result the *SMD* values for water and emulsions atomization are different.

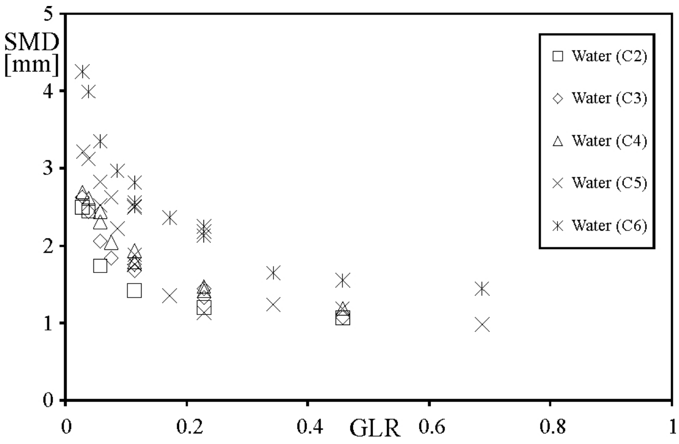

Figure 1. *SMD* as a function of *GLR* for water atomization

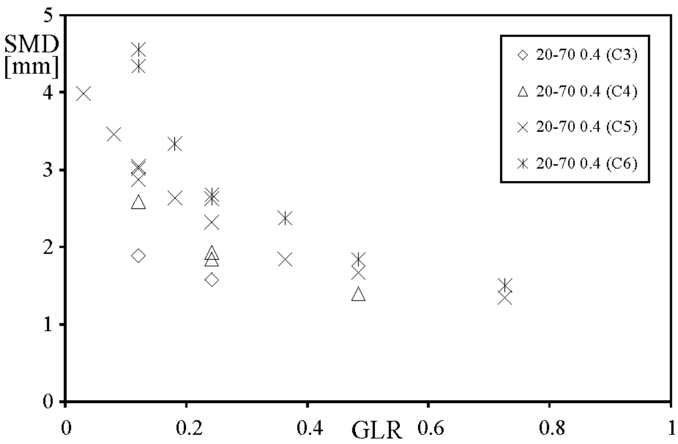

Figure 2. Exemplary plot of *SMD* as a function of *GLR* for 20-70 0.4 emulsion atomization

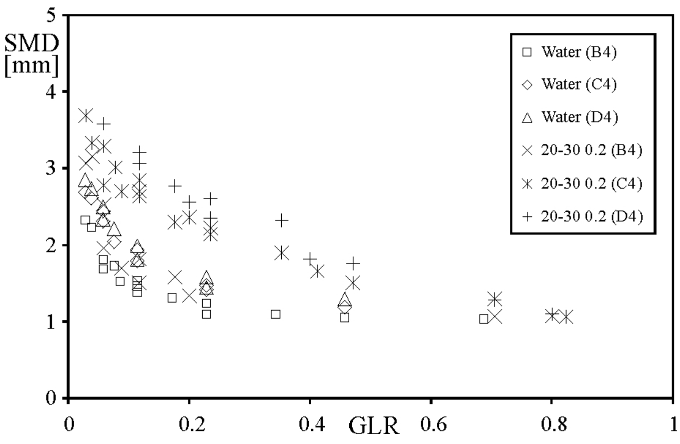

Figure 3. *SMD* vs. *GLR* for water and 20-30 0.2 emulsion

At a constant gas mass flow rate the increasing of liquid mass flow rate in the result produces larger droplets (as shown in Figure 3). In general, *SMD* exhibits a tendency to decrease with increasing *GLR*. At high values of *GLR*, atomization is complete within a short distance from the discharge orifice. In the cases of larger diameters of nozzle outlet (5 and 6 mm) liquid and gas flow with relatively small velocities, consequently, the liquid flows as a continuous body of cylindrical form. The jet was difficult to atomize. At low values of *GLR*, the jet disintegration into large drops was observed. The data obtained in present study have shown that the increasing of the atomizing gas mass flow will reduce the spray's *SMD* at constant liquid mass flow value.

In Figure 4 the exemplary relation between *SMD* and *GLR* for emulsion with increasing oil volume fraction is shown. As the oil content increases, its viscosity increases, consequently the breakup tendency decreases that results in larger *SMD* values. Experimental errors do not exceed 30%. The effect of nozzle diameters is smaller at *GLR* values over about 0.8. It has been suggested that the effect may be disregarded for atomization process at larger values of *GLR*.

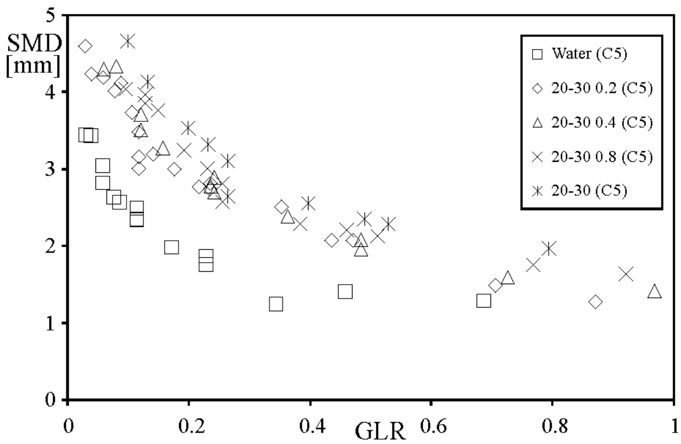

Figure 4. *SMD* vs. *GLR* for emulsion with increasing of oil volume fraction

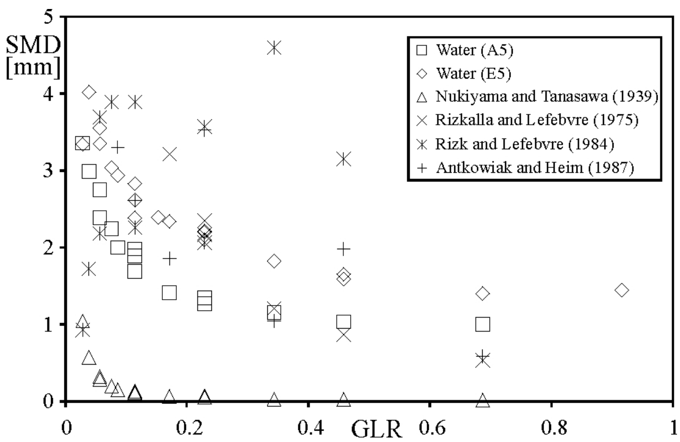

Figure 5. *SMD* as a function of *GLR* resulted from various studies

In the next stage of analysis the results of present study have been compared with those of representative studies in the literature (Figure 5). The comparison of the *SMD* values with the literature data is difficult for the sake of different constructions of investigated atomizers. The obtained results are in better approach to correlations given by Rizkalla and Lefebvre [5] and Antkowiak and Heim [8]. The correlation proposed by Nukiyama and Tanasawa [4] gives the understated values of *SMD* at values of *GLR* investigated and is probably correct at higher values of *GLR*. The droplets diameters produced by the investigated nozzles did not agree with the results published by Sakai *et al*. [6]. The equation of Rizk and Lefebvre [7] gives large dispersion of points. All of these correlations proposed have shown that *SMD* is decreasing with increase of *GLR*, but not all of them take into account nozzle diameters. Effect of nozzle diameters is clear and should be taken into consideration (in investigated range of nozzle diameters and *GLR* values). The investigations have shown that *SMD* is decreasing with decrease of nozzle diameters.

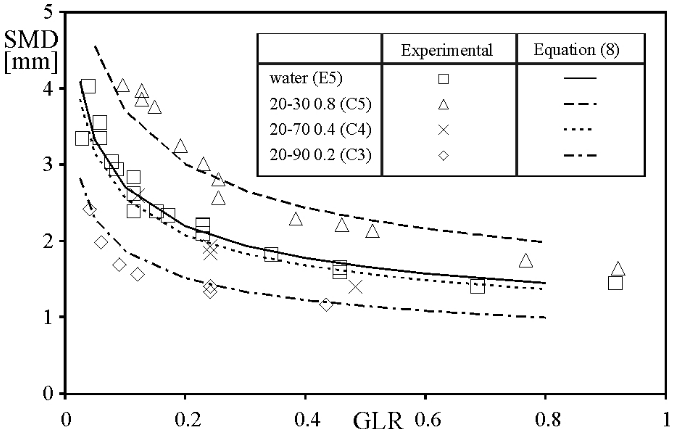

Figure 6. Experimental and correlations values of *SMD* as a function of *GLR*

Finally in analysis empirical correlation for *SMD* has been proposed. The analysis has shown that *SMD* is dependent on *GLR*, nozzle geometry and liquid characteristics. The empirical equation for *SMD* has been derived as follows:

$$SMD = A\frac{d_{out}^{1.14}}{d_{in}^{-0.56}}\frac{\mu_L^{0.12}}{\mu_G}GLR^{-0.30} \qquad (8)$$

where *A* is a function of nozzle internal geometry, surface tension and other parameters influencing atomization process. For investigated systems *A* was equal to $8.55 \cdot 10^{-4}$. In the equation Φ_{oil} is hiding inside liquid viscosity. The correlation has been compared with experimental data and presented in Figure 6. Equation (8) is valid for all investigated liquids at investigated *GLR* values and outlets diameters of nozzle.

SUMMARY

The experimental results showed that the changes in geometries of a nozzle lead to the significant changes in spray characteristics. The results of analysis are presented by the relationships of *SMD* as a function of *GLR*. The *SMD* for all investigated geometries is decreasing with increase of *GLR* value. It can be seen that *GLR* is a key parameter in determining the quality of atomization. The investigations have shown that *SMD* is decreasing with increase of liquid and nozzle outlets diameters. The differences between characteristics of atomization for water and emulsions, as well as the influence of emulsion composition on the droplet sizes, have been observed. The results showed that the *SMD* is dependent on a content of oil in emulsions. The empirical equation for *SMD* has been proposed.

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NOMENCLATURE

A	surface area	m^2
GLR	gas-to-liquid ratio by mass	-
SMD	Sauter mean diameter	m
$\dot{V}$	volumetric flow rate	m^3/s
d	diameter	m
$\dot{m}$	mass flow rate	kg/s
p	pressure	Pa
Φ	volume fraction	m^3/m^3
α	spray angle	deg
σ	surface tension	N/m
ρ	density	kg/m^3
μ	viscosity	Pa s

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