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EFFECT OF POLYMER ADDITION ON THE CHARACTERISTICS OF EFFERVESCENT ATOMIZATION

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ABSTRACT

The paper contains the results of experimental investigation of air-water and air-polymer solutions atomization process in effervescent nozzles with internal mixing obtained by the use of the digital microphotography method. In experiments the different aqueous solutions of polyethyloxide (PEO) of different molecular weight have been used. The observations were carried out at liquid flow rate changed from 0.0014 to 0.011 [kg/s] and gas flow rate from 0.0003 to 0.0013 [kg/s]. It corresponded to gas to liquid mass ratio values from 0.028 to 0.92. The analysis of photos shows that the droplets which have been formed during the liquid atomization have very different sizes. The smallest droplets have diameters of the order of ten micrometers. The differences between characteristics of effervescent atomization for the different types of PEO used have been observed. The present study confirmed the previous reports which suggested that the changes in character of a flow are connected with the rheological properties of liquid, two-phase flow character, flow rates of liquid and gas phases. The effects observed lead to significant changes in the quality of the spray produced by nozzle.

INTRODUCTION

Effervescent atomization is a method of twin-fluid atomization that involves bubbling a small amount of gas into the liquid before it is ejected from the atomizer. The technique of bubbling gas directly into the liquid stream inside the atomizer body is essentially different from other methods of twin-fluid atomization (either internal or external mixing) and leads to significant improvements in performance in terms of smaller drop sizes and/or lower injection pressures. The effervescent nozzles fall into the category of internal mixing nozzles. Atomizing gas is injected into the liquid at very low velocity to form a bubbly two-phase mixture upstream of the discharge orifice. The schematic atomization mechanism in effervescent nozzles (Figure 1) was proposed by Roesler and Lefebvre [1,2]. The separate injection of gas allows the number, size, and spatial distribution of bubbles to be controlled in effervescent designs. This method of atomization is not restricted to volatile liquids or liquids that can hold a substantial amount of dissolved gas. Neither is the choice of gas restricted to those that can dissolve readily into the liquid. Furthermore, the bubble formation process does not involve mass diffusion of dissolved gas to the nucleation sites, as in dissolved gas atomization, or energy diffusion necessary for evaporation, as in flash atomization. These inherently slow processes necessitate the use of expansion chambers in flashing and dissolved gas systems, limitations not found in effervescent atomizers. Effervescent atomizers have so far been found useful for gas turbine fuel injectors, for internal combustion engines and for consumer product sprays. Atomization of liquids is a core element in many chemical engineering processes such as agglomeration, spray drying, and spray painting [3-9].

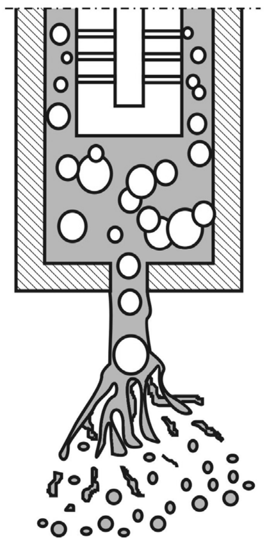

Figure 1. Schematic atomization mechanism observed by Roesler and Lefebvre [1,2]

The most important variables are the spray angle, covering of surface, the mean droplet size and the droplet size distribution of the liquid sprayed [9-11]. Many processes use atomizers to deliver fluids. In certain applications, the droplet size distribution must have a particular form (narrow, wide, few large droplets, few small droplets, etc.) for optimal operation. Knowledge of the effect of variations in fluid physical properties, atomizer geometry, and atomizer operating parameters on droplet size distribution is to be realized [12]. For example, droplet size control is essential in order to produce pharmaceutical products with the desired properties [13]. The Sauter Mean Diameter (*SMD*) is often of use in applications where the active surface or surface area is important (eg. atomization, catalysis or combustion). The *SMD* is calculated as the ratio:

$$SMD = \frac{\sum_i n_i d_i^3}{\sum_i n_i d_i^2} \qquad (1)$$

The most of graphic plots have presented the dependence of *SMD* as a function of gas to liquid mass flow rates ratio (*GLR*), while *GLR* is defined as follows:

$$GLR = \frac{\dot{m}_G}{\dot{m}_L} \qquad (2)$$

High molecular polymers added to solvent sprayed (water) involve the changes in the viscosity of liquid and in the characteristics of a flow. The other parameters such as the size of droplets, the spray cone, the distribution of liquid in stream of droplets of spray are changed too. The results show that there are complex, but qualitatively predictable interactions between the rheological properties of the liquids and the pressure drop values. Further, it is clearly demonstrated that low concentrations of polymer additives may have profound effects on the spray pattern produced by typical spray systems.

In the present paper the results of experimental observations on polymers solutions atomization process in effervescent nozzle using the digital microphotography method have been presented.

EXPERIMENTAL APPARATUS

The schematic diagram of experimental apparatus was shown in an earlier publication [11]. The nozzles consist of four main components: liquid and gas supply ports, a mixing chamber where the gas is bubbled into the liquid stream, and an exit orifice. The nozzles used in this study have a diameter of outlet (d_{out}) 3, 4, 5 and 6 [mm]. Inside-out gas injection geometry (gas flows inside the aerator tube and bubbles outward into the surrounding liquid) has been used. The multi-hole aerator presented in Figure 2 (aerator tube diameter d_A of 15 mm) has 3 holes of diameter d_h of 2.6 mm.

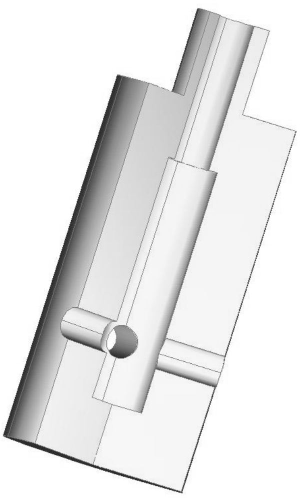

Figure 2. Aerator tube

The test fluids used in this study were water solutions of poly(ethylene oxide) (PEO) with concentration of 0.0015 [kg polymer/kg solution] presenting polymers with molecular weight (*MW*) from $1 \cdot 10^6$ to $8 \cdot 10^6$ [g/mol]. The PEO used was supplied from Aldrich Chemical. The aqueous solutions studied were power-law fluids

$$\tau_w = K(\gamma_w)^n \qquad (3)$$

where τ_w is the wall shear stress, K describes the consistency index, γ_w is the shear velocity at a wall and n describes the flow behaviour index. The characteristics of investigated fluids are presented in Table 1.

Table 1. Characteristics of the liquids studied

	Liquid				
Denotation	PEO	PEO	PEO	PEO	PEO
M_w [kg/kmol]	$1 \cdot 10^6$	$2 \cdot 10^6$	$4 \cdot 10^6$	$5 \cdot 10^6$	$8 \cdot 10^6$
c [ppm]	1500				
ρ [kg/m^3]	998				
K [Pa·s^n]	$2{,}6 \cdot 10^{-3}$	$2{,}9 \cdot 10^{-3}$	$4{,}15 \cdot 10^{-3}$	$4{,}9 \cdot 10^{-3}$	$8{,}1 \cdot 10^{-3}$
n	0,95	0,95	0,94	0,94	0,89

The photographs have been obtained using a Canon 1D Mark III camera with exposure time of 1/8000 s. The photographs were analyzed using Image Pro-Plus delivered by Media Cybernetics. The observations were carried out at liquid flow rate changed from 0.0014 to 0.011 [kg/s] and gas flow rate from 0.0003 to 0.0013 [kg/s]. It corresponded to gas to liquid mass ratio values from 0.028 to 0.92.

RESULTS AND DISCUSSION

Exemplary results of the visualization of atomization are shown in Figure 3. The differences between air-water and air-polymers solutions atomization have been observed. The development of the spray passes through several stages described by Lefebvere [9] such as dribble, distorted pencil and fully developed spray. Additionally, the following stages were distinguished: the filaments with built-in droplets, the filaments with built-in bubbles, bubbles connected by filaments and satellite bubbles. These observations are in agreement with the observations of Geckler and Sojka [14]. The stages are the result of mechanism of effervescent atomization but are not characterized by the typical bubble expansion mechanism or the trunk with branching ligaments mechanism. Owing to the rheological properties of the liquid, an annular net-like structure is observed over a wide range of *GLR*s. The observations suggested that the stage of spray development is strongly affected by the rheological properties of liquid atomized. The addition of polymer molecules changes the rheology of the bulk fluid influencing interfacial break up. Rheological parameters of investigated polymers solutions retard the formation of satellite drops. Addition of polymers to solutions causes the creation of stable bubbles.

In Figure 4 the relations between *SMD* and liquid and gas volume rates for different outlet diameters are shown. The stage of fully developed spray proceeded quickly for nozzles with smaller diameter of outlet. It is a result of higher values of gas flow rate in smaller diameters of orifices. Higher values of the velocities cause the acceleration of jet disintegration.

The data obtained in this study have been shown that increasing the atomizing gas mass flow will reduce the spray's *SMD* at constant liquid mass flow value. It has been shown that nozzle outlet diameter has effect on produced droplets. The atomization quality deteriorates with increases in diameters of liquid and nozzle outlets. The effect of nozzle diameters is smaller for *GLR* values over about 0.8. It has been suggested that the effect can be disregarded for atomization process made at higher values of *GLR*. The same effect has been observed for all investigated polymers solutions.

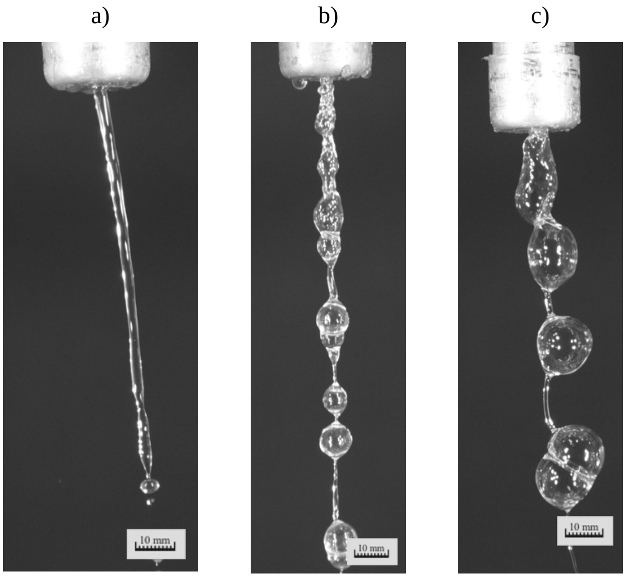

Figure 3. Exemplary photos of atomization:
a) water, d_{out} = 3 mm, m_G = 0.0003 [kg/s], m_L = 0.0056 [kg/s],
b) PEO-5, d_{out} = 3 mm, m_G = 0.0013 [kg/s], m_L = 0.0084 [kg/s],
c) PEO-8, d_{out} = 5 mm, m_G = 0.0006 [kg/s], m_L = 0.0056 [kg/s]

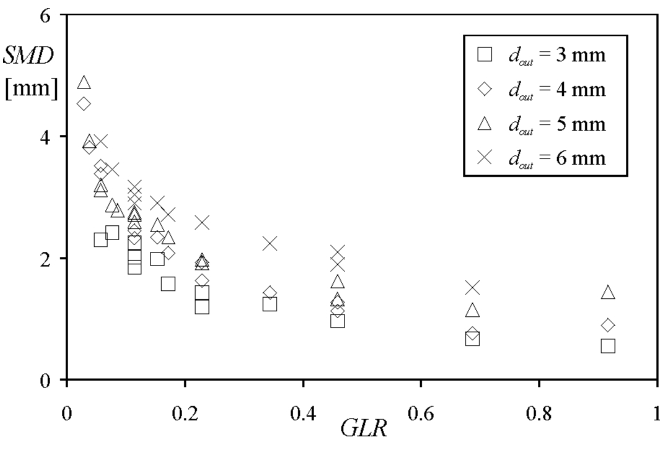

Figure 4. Exemplary plot of *SMD* as a function of *GLR* for water atomization

The experimental results show that *SMD* is a non-linear function of *GLR*, with mean drop size decreasing rapidly as *GLR* is increased from zero to around 0.03 and thereafter decreasing at a slower rate with further increase in *GLR*. Our studies have shown that at low *GLR*s (<0.03), atomizers with low values of the ratio of the final discharge orifice area to the total area of the aerator holes (A_o/A_h) (0.45 for d_{out} = 3 mm) produced finer sprays than those beeing produced by atomizers with high values of A_o/A_h (0.8 for d_{out} = 4 mm, 1.24 for d_{out} = 5 mm and 1.79 for d_{out} = 6 mm). In all investigated cases *GLR* played a key role in the mean droplet size. The *GLR* is an important operating parameter in most applications since it is desirable to minimize the amount of atomizing gas supplied while maintaining a small mean drop size. The low air consumption may have an important influence in processes where the air consumption has to be limited due to product characteristics.

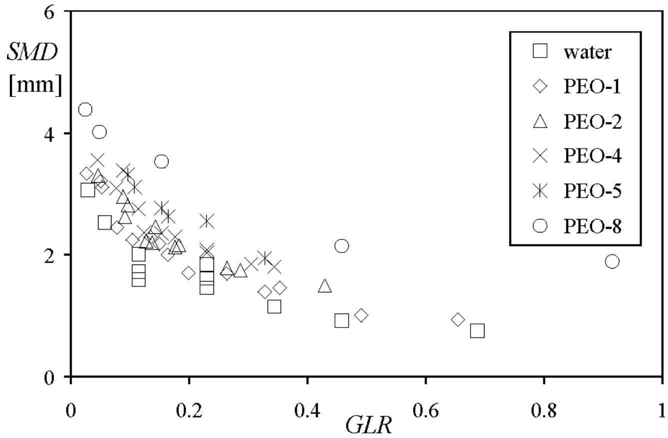

Figure 5. Exemplary plot of *SMD* as a function of *GLR* for atomizer with d_{out} = 3 mm

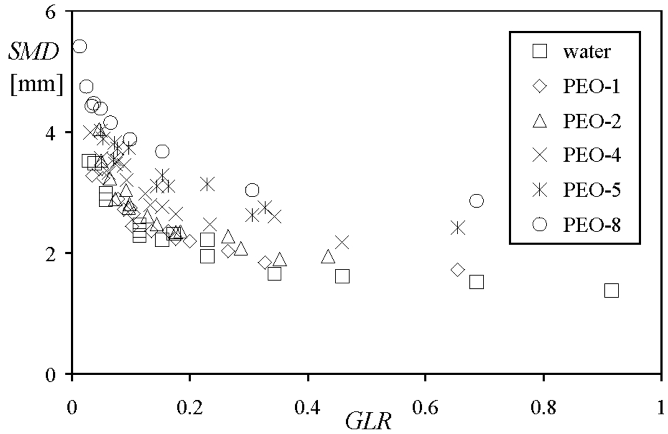

Figure 6. Exemplary plot of *SMD* as a function of *GLR* for atomizer with d_{out} = 5 mm

The comparison of obtained photos shows that droplets formed during the PEO atomization have different sizes in comparison with droplets sizes at water atomization. In the result the *SMD* values for water and polymers atomization are different. Exemplary plots of *SMD* vs. *GLR* for different geometries of atomizer are presented in Figures 5 and 6. It has been shown that the PEO added to water has an effect on *SMD* value. The *SMD* increased as the liquid viscosity increased by increasing the polymer molecular weight. This effect is in agreement with the measurements of Geckler and Sojka [14] and Lee and Sojka [15]. The same effect was observed for other type atomizers [16]. It is clear that molecular weight of PEO affects *SMD* and is independent of nozzle construction. The comparison of the *SMD* values with the literature data is difficult for the sake of different constructions of investigated effervescent atomizers and small number publications for polymers solutions effervescent atomization.

The experiments showed that the atomization quality depends on gas and liquid flow rates, type of atomizing liquid (molecular weight of polymer) and the atomizer construction used. It has been shown that the resulting sprays were strongly dependent on the nozzle geometry. The effervescent atomizer with gas-liquid internal mixing offers several advantages over conventional types of atomizer, such as equivalent droplet sizes at reduced atomizing gas consumption, compared to what is obtained in pneumatic atomizers [11], and the reduced clogging as the result of a construction of nozzle.

SUMMARY

The experimental observations on polymers solutions atomization process in effervescent atomizers have been studied. The different atomization stages were observed. The results of analysis are presented by the relationships of *SMD* as a function of *GLR*. *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 differences between characteristics of atomization for water and PEO water solutions have been observed. The experimental data have shown that the changes in rheological properties of a liquid phase lead to the significant changes in spray characteristics. The influence of molecular weight of PEO on the droplet sizes has been observed. The analysis of the photos of water and PEO atomization process showed that the *SMD* is dependent on: rheological properties of liquid atomized, *GLR* and construction of atomizer.

ACKNOWLEDGMENT

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NOMENCLATURE

A	surface area	m^2
GLR	gas-to-liquid ratio by mass	-
K	consistency factor	$Pa\ s^n$
M_w	molecular weight	kg/kmol
SMD	Sauter mean diameter	m
c	concentration	ppm
d	diameter	m
$\dot{m}$	mass flow rate	kg/s
n	flow index	-
ρ	density	kg/m^3

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