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The effect of orifice shape and the injection pressure on enhancement of the atomization process for pressure-swirl atomizers

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ABSTRACT

The following paper presents results of studies on the atomization process of water in pressure-swirl atomizers with different shapes of orifice using a laser diffraction technique. The effect of the shape of the orifice and the injection pressure on the droplet size distributions and mean droplet diameters was analyzed. The results obtained showed that droplet size decreases with an increasing injection pressure and droplet size distributions are expanded. The smallest droplet diameters were obtained by atomization in profiled and conical shaped orifice atomizers, however the largest droplet diameters were achieved for plain orifice atomizers. The analysis of the interfacial surface produced by the atomizers has shown that the greater enhancement of the atomization process had occurred using profiled and conical shaped orifice atomizers compared with plain orifice atomizers. The correlation for the Sauter mean diameter as a function of the Reynolds number and the ratio of orifice length to diameter has been proposed. The paper is related to agricultural water management. The data obtained are important from the point of view of the design of atomizers, agricultural treatments and crop protection.

1. Introduction

Pressure-swirl atomizers have many applications especially in the chemical industry, trade and agriculture (Nasr et al., 2002; Park and Heister, 2010; Santolaya et al., 2010; Chaudhari et al., 2013). These types of atomizers are the most commonly used in orchards and vineyards (Laryea and No, 2003; Endalewa et al., 2010; Belhadef et al., 2012). They are also applied in the processes of spray drying, cooling, coating, aircraft turbine engines, fuel engine injectors, sprinklers, fire protection systems etc. (Moon et al., 2008; Lee et al., 2010; Mezhericher et al., 2010; Tesar, 2014). These devices are characterized by simplicity, high efficiency of atomization and reliable combustion stability (Lee et al., 2010). A better mixing efficiency and reduction of the pollution problem in the combustion chambers can be achieved through the application of the appropriate pressure-swirl atomizers (Lee, 2008). Atomization plays an important role in the cooling systems, due to excellent heat and mass transfer. The latent heat exchange is a major factor in the cooling performance when a large number of droplets is injected into the surrounding ambient gas. As a result, spraying systems are widely used in nuclear power engineering (pressurizer and the reactor core spray system) (Ochowiak and Broniarz-Press, 2011; Lan et al., 2014).

The understanding of the disintegration mechanism in the atomizers and finding the optimal conditions has fundamental significance in the design of atomizers. Despite the great popularity of pressure-swirl atomizers, it has not been fully explained what factors affect the mean droplet diameters and how they cause atomization. Based on previous studies, the following factors can be distinguished: liquid properties, differential pressure between the

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liquid and the surrounding ambient gas, gas properties and the dimensions of the atomizer (Ballester and Dopazo, 1996; Tratnig et al., 2009; Tratnig and Brenn, 2010; Negeed et al., 2011; Dorr et al., 2013). In agriculture, the properties of the spray droplets have an impact on the effectiveness and risks associated with use of pesticide (Dorr et al., 2013). In the pressure-swirl atomizer liquid is supplied to the nozzle chamber along a tangential inlet of a sufficient centrifugal force, which creates a strong vortex or swirl motion. This vortex maintains the air core inside the chamber. The stability of an air core (constant shape and height) is one of the most important characteristics which distinguish pressure-swirl atomizers.

Li et al. (2011) have studied the droplet size distribution of fuel droplets atomized in pressure-swirl atomizers at ambient pressure of 0.1 and 0.4 MPa. The several diagnostic laser techniques used in the study included a method based on laser diffraction. The results showed that the droplets in the external zone of the atomized stream exhibit a larger diameter than droplets in the internal zone. This phenomenon can be partly attributed to the effect of the environment. The interaction of ambient air flow decreases with increasing pressure, causing a significant effect on the dynamics of the spray droplet size distribution. The droplets in the external zone have a larger diameter than those near the spray axis. Although the droplets diameters at the central zones are smaller, the density of the spray is much bigger than in the external zones.

The most important general property of the spray is expressed by the Sauter mean diameter (*SMD*, D_{32}) of the droplets. *SMD* defines the relationship:

$$SMD = \frac{\sum_{i=1}^{i=n} N_i d_i^3}{\sum_{i=1}^{i=n} N_i d_i^2} \qquad (1)$$

where i is the considered size range, N_i is the number of droplets in size range i, and d_i is the droplet diameter (Lefebvre, 1989; Xie et al., 2013; Hemati et al., 2015).

Sanghoon and Sungwook (2014) have studied the influence of injection pressures up to 30 MPa on Sauter mean diameter and droplet size distribution in a gasoline direct injection. They found that increasing injection pressure from 5 to 20 MPa led to decrease in *SMD*. However, an injection pressure above 20 MPa did not result in any significant reduction in Sauter mean diameter. Based on the droplet diameter distribution, a significant role of injection pressure in droplet breakup was also observed.

A method based on a laser diffraction measurement allows for the determination of the apparent mean droplet diameter. *SMD* is the mean diameter of the droplets containing information about the ratio of volume to the area of all measured droplets (Gholam Samani et al., 2012). Another important diameter is D_{V90}, which is the representative diameter of droplets where 90% of the total volume of the liquid is found in the droplets with diameters smaller than the mean droplet diameter of D_{V90}. Both, *SMD* and D_{V90} are important parameters in the atomization process and the formation of compound, for example for internal combustion engines or in catalysis (Lan et al., 2014).

The value of the Sauter mean diameter of the droplets depends on many factors, such as the surface tension, density and viscosity (Chapple et al., 1993; Butler Ellis et al., 1997; Broniarz-Press et al., 2014). Many authors (Radcliffe, 1960; Rizk and Lefebvre, 1985; Suyari and Lefebvre, 1986; Wang and Lefebvre, 1987; Lefebvre, 1989; Bolszo et al., 2010) have modified the formula for *SMD*. One of the first models for *SMD* was presented by the Radcliffe formula (Radcliffe, 1960):

$$SMD = 7.3\sigma_L^{0.6}\nu_L^{0.2}\dot{m}_L^{0.25}\Delta P_L^{-0.4} \qquad (2)$$

where σ_L – liquid surface tension, ν_L – liquid kinematic viscosity, $\dot{m}_L$– mass flow rate of liquid, ΔP_L – differential pressure between the sprayed liquid and the surrounding gas.

Lefebvre (1989) proposed a correlation for simplex atomizers in the following form:

$$SMD = 2.25\sigma_L^{0.25}\mu_L^{0.25}\dot{m}_L^{0.25}\Delta P_L^{-0.5}\rho_A^{-0.25} \qquad (3)$$

where μ_L – liquid dynamic viscosity, ρ_A – air density.

Wang and Lefebvre (Wang and Lefebvre, 1987; Bolszo et al., 2010) presented the equation for *SMD* in the form:

$$SMD = B\left(\frac{\sigma_L\mu_L^2}{\rho_A\Delta P_L^2}\right)^{0.25} t\cos\theta^{0.25} + C\left(\frac{\sigma_L\rho_L}{\rho_A\Delta P_L}\right)^{0.25} t\cos\theta^{0.75} \qquad (4)$$

where t – film thickness at the atomizer exit (Suyari and Lefebvre, 1986), θ – spray cone half-angle.

Despite the numerous experimental studies concerning the mechanism of jet disintegration for pressure-swirl atomizers, the effect of geometry is still considered and tested (Rizk and Lefebvre, 1985). Li and Tankin (1991) showed that the use of swirling components is very important to improve efficiency and mixing inside the atomizer. The jet breakup of liquid flowing out from the atomizer in the form of small droplets causes an increase in the interfacial surface. It was found that the swirl motion and turbulences at the atomizer exit may affect the dispersion of drops and the propagation rate of spray (Hardalupas and Whitelaw, 1995).

The decrease of *SMD* followed by the decrease in the ratio of orifice length to diameter l_0/d_0 is connected with the shorter breakup of the spray that accompanies higher turbulence intensity. Therefore, the length of the orifice is one of the important parameters in the design of atomizers (Mandal et al., 2008; Lee et al., 2010). The reduction of l_0/d_0 can enhance the atomization process, but this is not related to the distance from the atomizer. The phenomenon of stream contraction occurs in the atomizer exit and disappears with increasing l_0. The liquid in the swirl chamber, due to the tangential and axial velocity components, creates a thin conical film. Although the geometry of atomizer is simple, the hydrodynamic processes inside the atomizer are complex.

The internal geometry of the atomizer plays an important role in obtaining the required quality of spray. The effect of the atomizer geometry and the injection pressure on the spray formation was presented by Ali and Aziz (2007). For the differential pressure of liquid-surrounding gas in the range from 3.0 to 10.0 MPa, a point-tip needle used in conjunction with a high swirl intensity results in formation of a lower discharge coefficient, thinner liquid film, larger spray angle, and smaller drop sizes than extrude-tip and round-tip needle. Durdina et al. (2014) studied the characteristics of atomization for pressure-swirl atomizers of two different geometries. The significant effect of atomizer construction on the atomization process was observed.

The conducted experimental research reported here focused on the intensification of the atomization process and the improvement of spray properties produced by pressure-swirl atomizers by modifying the shape of the orifice and changing the injection pressure of the liquid. Moreover, the size of interfacial surface of dispersed liquid – surrounding gas has been analyzed.