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EFFERVESCENT ATOMIZER FOR ATOMIZATION OF SUSPENSIONS CONTAINING LARGE PARTICLES

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ABSTRACT
Single-hole effervescent atomizer in outside-in gas injection configuration is designed for spraying of waste fuels. An experimental study of atomization process is performed on cold test bench. The waste fuel is simulated using light heating oil (LHO) loaded with solid spherical particles in the size range 1 to 1.5 mm and mass concentration 10 %. Our tests supported by simple calculation show negligible effect of the particles loaded in the suspension on the final spray. Influence of gas to liquid ratio by mass (GLR) on spray cone angle is evaluated using spray photography.
The spray cone angle of a single-hole effervescent atomizer is extended by a swirl of the gas-suspension mixture in front of the exit orifice. Three atomizers were fabricated to test the effect of swirl chamber on the spray: atomizer without swirler, atomizer with moderate swirler and atomizer with intense swirler. Swirling the mixture leads to a significant increase of the spray cone angle at low GLR. An increase of the gas mass fraction in the mixture inhibits the swirl action on the spray shape. The swirl effect diminishes with GLR rising above 15 %.

INTRODUCTION

Worldwide grow of energy consumption along with decline of primary fuel resources escalates a demand of alternative fuels (biofuels, waste fuels). Recent analysis of waste products treatment shows that European Union could prefer their combustion against their recycling. Also for some industrial process by-products, their combustion can be an effective way of their utilization.

The waste liquids (e.g. waste oils) often have low heating value, variable physical properties and contain solid particles. It is necessary to account for these features when selecting and designing an appropriate atomizer and atomization mechanism. One of very promising technics is effervescent atomization [1]. In effervescent atomization, the gas (preferably air or steam) is injected into the bulk liquid at some point upstream of the injector orifice. The two fluids form a two-phase mixture, flow downstream and exit the atomizer through an orifice to the ambient atmosphere forming a spray. The liquid is broken up by the gas bubbles into thin shreds and ligaments. When the gas bubbles emerge from the nozzle they 'explode' and shatter the surrounding liquid shreds and ligaments into small droplets. Major advantage of effervescent atomizers is their relative insensitivity to fuel physical properties and ability to perform a good atomization over a wide range of operating conditions. Furthermore the E-atomizers can have larger orifice than conventional atomizers which alleviates clogging problems and facilitates atomizer fabrication [2]. In combustion applications they lead to lower pollutant emissions due to presence of the air in the spray core.

Atomization process of liquids containing solid particles (suspensions) differs from atomization of pure liquids. During the disintegration process the interactions among the three different phases (gas, liquid, solid) as well as the rheological properties of the suspension which depend strongly on the solid particles content, can play an important role. Understanding of the suspension atomization process facilitates control of droplets size in the spray and therefore the process quality which finally influences exhaust gas emissions. Several studies can be found on atomization of suspensions using effervescent atomizer [3-8] but further research can improve our knowledge in this area.

EXPERIMENTAL APPARATUS

The effervescent atomizers were tested on cold test bench with a mixing device for preparation of suspension of solid particles with LHO.

Atomizers

Design of atomizer for combustion application has to fulfil several basic demands. The produced spray has to be fine and stable in defined turn-down ratio to provide good combustion efficiency and low content of pollutants in the exhaust gases. Nozzle construction must prevent clogging and should be easy fabricated. Additional requirement is a suitable and preferably controlled spray cone angle.

Our tests with LHO loaded with large solid particles and calculations bellow show no significant influence of the particles on atomization and on size of liquid droplets. It outlines that design of the atomizer for suspension with large particles can be made according the same rules as the design of atomizer for pure liquid. Main problem of the suspension discharge can be clogging. All flow cross-sections must be designed sufficiently large and with gradual cross-section changes.

The atomizer design is based on results acquired in [9]. A single-hole, plain orifice atomizer in the "outside-in" gas injection configuration is used, see Fig. 1. It consists of a cylindrical body in which an aerator tube with internal diameter d_c = 14 mm is inserted. The liquid (suspension) enters the central orifice of the aerator from the left side, while the air is injected into the liquid, through a set of 40 holes with diameter d_a = 1 mm in the aerator body. Three different atomizers were designed; one version without swirler and two swirl atomizers with swirl in the front of the exit orifice. Distance of the first row of aeration holes from the discharge orifice is l_c = 33 mm for atomizer without swirler and 53 mm for atomizer with swirl insert. The span length, Δl, between the first and the last row is 90 mm.

Effervescent sprays have substantially wider spray cone angles than those produced by plain-orifice pressure atomizers [10]. The spray cone angles were found to vary with atomizer operation conditions (inlet pressure and GLR) as well as with atomizer internal dimensions [11]. The cone half-angles of particular atomizers range between 10.5° - 14.4° at GLR 2 % and 8.8° - 11.9° at GLR 10 % for a range of inlet pressure 0.1 to 0.5 MPa. These values usually are not sufficient for combustion in the furnaces or turbines [1]. Several possibilities to widen the spray cone are known. Whitlow et al. [12] tested effervescent atomizer with multi-hole and annular orifice. Both the ways lead to reduction of dimensions of exit orifice cross-section and hence are not suitable for atomization of suspensions containing large particles. Usage of a deflector in the front of the exit orifice enables good control of spray cone angle but it also tends to choking by carbon. The most frequent way to enlarge cone angle is an addition of the tangential velocity component to the fluid prior to discharge. Tangential movement causes radial force on the liquid and finally formation of the liquid into wide hollow spray cone. Introduction of the tangential velocity component can be made by swirling of the single fluid, gas or liquid, at the atomizer entry, swirling of the two-phase mixture [13] or by external gas swirler after discharge. Flat-tangential and helical swirl chamber and swirling insert [13] were found in the literature. Helical swirl insert was chosen for our application.

Three different versions were designed; one atomizer without swirler and two swirl atomizers with different swirl intensity. The atomizer without swirler has aerator connected directly with an exit nozzle with discharge orifice diameter d_o = 3.5 mm and a length of 0.7 mm. There is a conical junction with the apical angle of 120° in front of the orifice. The swirl atomizers have a swirl insert placed between the aerator and the exit nozzle, see Fig. 1. The swirlers were designed with a view to a maximum swirl intensity keeping minimum swirler built-in length and large enough cross-section area. Swirl insert of atomizer I has 4 helical channels with cross-section 5.5×6 mm at mean diameter 32 mm with pitch 28 mm/thread. Atomizer II has 2 channels with cross-section 6×6 mm at mean diameter 32 mm with pitch 14 mm/thread. Exit orifice diameter, length and the apical angle were kept the same as in the previous case. The atomizers were continuously operated in vertical position of main axis during tests.

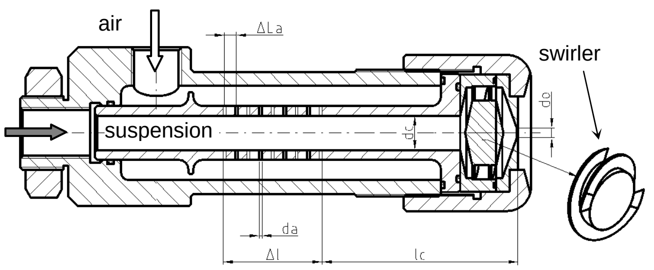

Fig. 1: Schematic layout of the research atomizer.

Test bench

A schematic layout of the experimental facility is shown in Fig. 2. The cold test bench was equipped with a mixing device to discharge solid particles into LHO. Using this device a suspension with controlled content of solid particles of desired size was studied. Oil is supplied by a gear pump (14) from a main fuel tank (16) into tank (19) through filters (15), control valves (9, 10) and flow meters (6). A chiller (11) ensures constant oil temperature and hence also its viscosity. Solid particles are dosed into the pressurized tank (19) and a mixture formed of LHO and the particles is homogenized using a propeller. The suspension is pressurized by a compressed air and introduced into the atomizer (7). The compressed air is delivered, either from the central plant, or from a two stage compressor (1) through the air chamber (2), filters (4), control valve (5) and flow meters (6) into the atomizer. Sprayed suspension is collected in a vessel (12) and returned to the mixing device by the pump (13). The collector is connected to an oil mist separator that keeps the spray zone free of aerosol but does not disturb the spray. Pressure (3, 8) and temperature (17) readings are taken at the atomizer inlets for both the suspension and the air.

Simulation of the waste liquid

A suspension to substitute the waste liquid was prepared by mixing of light heating oil with solid particles in mass concentration 10 % of the particles. The pure LHO has density 874 kg/m^3, dynamic viscosity 0.0185 N.s/m^2 and surface tension 0.0297 N/m at room temperature. Particles used were Polystyrene beads with density of 938 kg/m^3. Granularity was 1.0-1.5 mm and the mean particle size 1.2 mm. Particles were practically spherical. Ubbelohde viscosimeter was used to measure fluid viscosity (uncertainty value 7 %), detach method was used to measure the surface tension (uncertainty value 5 %). Physical properties of the particles were taken from their technical specification sheets.

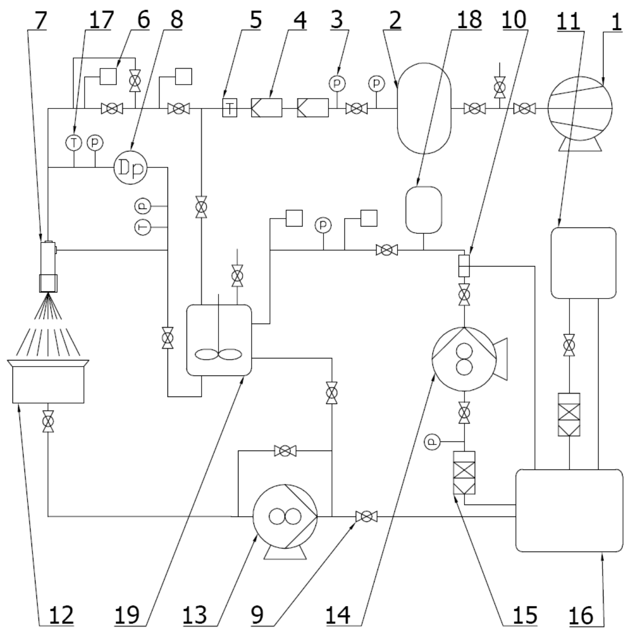

Fig. 2: Cold test bench.

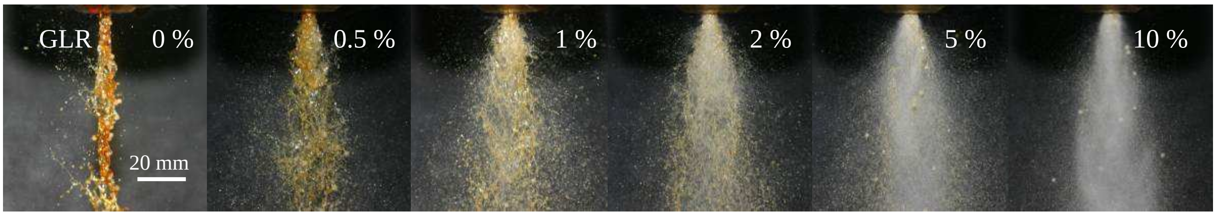

Fig. 3. Spray structure of atomizer without swirler at air gauge pressure 0.05 MPa with GLR varied.

SPRAY CONE HALF-ANGLE

Figure 3 shows photographs of the spray of atomizer without swirler at air gauge pressure 0.05 MPa with GLR varied. Discharge of liquid without gas support (GLR = 0) i.e. pressure atomization is connected with very pore spray. Already very small amount of atomizing air significantly improves atomization and widens the spray cone angle. Large ligaments of liquid are produced at exit orifice and consequently broken up into smaller liquid volumes and droplets. Increase in GLR shortens the ligaments and they virtually disappear at GLR higher then 5 % where only droplets are seen after the discharge orifice. The photographic observation of suspension discharge does not show any agglomeration of the particles in the spray. We did not register any agglomeration even in the case of elevated concentration of solids up to 50%. The solids are dispersed in all the spray volume. Only in the case of higher GLR the particles tend to occur more preferably at spray edge. For evaluation of influence of solids on atomization it is particularly interesting to know a number of discharged solid particles compared to total number of droplets; it will be discussed later.

The photographs of the spray were used for evaluation of the spray cone angle of all three atomizers. Influence of GLR and effect of swirl intensity on the spray cone angle for all three atomizers at inlet pressure 0.5 MPa is seen in Fig. 4. Atomizer without swirler (plane orifice) produces spray with maximum cone half-angle about 20° at GLR 10 %. In the case of GLR = 0 the stream of discharged liquid has almost zero divergence. Atomizers with swirler gives spray with wide cone angle already at GLR = 0. The spray has a form of hollow thin conical sheet. Introduction of atomizing air leads to reasonable increase in the cone angle of the atomizer I, with moderate swirler, up to GLR about 6 %. Continuing increase in GLR reduces the cone angle. Spray cone half-angle of atomizer II, with intense swirler, show monotonic decrease with GLR increase. Discharge of pure incompressible liquid (liquid-particle solution) differs from discharge of liquid-gas mixture. Gas flowing with critical velocity disturbs angular momentum of swirled mixture and converts all energy to the axial movement at the exit orifice. Larger spray cone angle at low GLR, where atomizer is operated at full power, and reduction of the spray cone angle with GLR rising is desirable feature of the atomizer for combustion application [14].

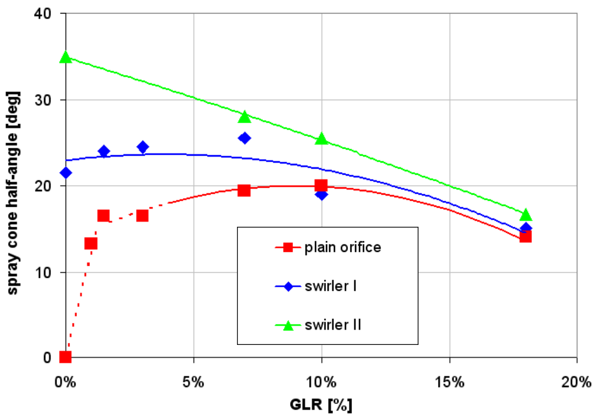

Fig. 4: Influence of mixture swirl and GLR on the spray cone half-angle.

MEAN DROPLET SIZE

Suspension of solid polystyrene particles and LHO is atomized using air. The particles are hydrophobic, so the size of discharged solids is similar to the original particle size, d_s. Volumetric concentration of solids in the suspension is defined as $v_s = V_s/(V_s + V_l)$. Number of solid and liquid particles per unit volume is:

$$N_s = \frac{6 \cdot v_s}{\pi \cdot d_s^3}, \quad N_l = \frac{6 \cdot v_l}{\pi \cdot d_l^3} = \frac{6 \cdot (1 - v_s)}{\pi \cdot d_l^3} \qquad (1, 2)$$

assuming for simplicity that liquid droplets are monosized with diameter d_l or taking d_l as mean volumetric diameter of the liquid droplets. Relative number of solid particles:

$$n_s = \frac{N_s}{N_s + N_l} = \frac{v_s}{v_s + R_d^3 (1 - v_s)} \qquad (3)$$

where R_d is ratio of solid and liquid particle diameters. Relative number of solid particles is calculated for several R_d values and variable concentration of solids in Fig. 5. Sauter mean diameter of final spray reads:

$$D_{32} = \sum_{j=1}^{N} D_j^3 \Big/ \sum_{j=1}^{N} D_j^2 = d_l \frac{1 - n_s + n_s \cdot R_d^3}{1 - n_s + n_s \cdot R_d^2} \qquad (4)$$

And relative change in D_{32} compared to the size of liquid droplets:

$$\frac{D_{32}}{d_s} = \frac{1}{R_d} \frac{1 - n_s + n_s \cdot R_d^3}{1 - n_s + n_s \cdot R_d^2} \qquad (5)$$

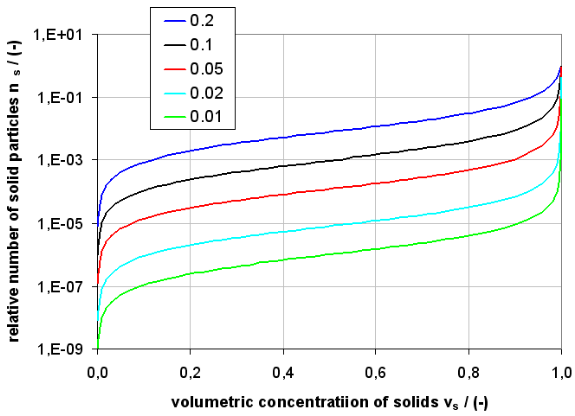

Fig. 5: Relative number of solid particles is calculated for several R_d values and variable concentration of solids.

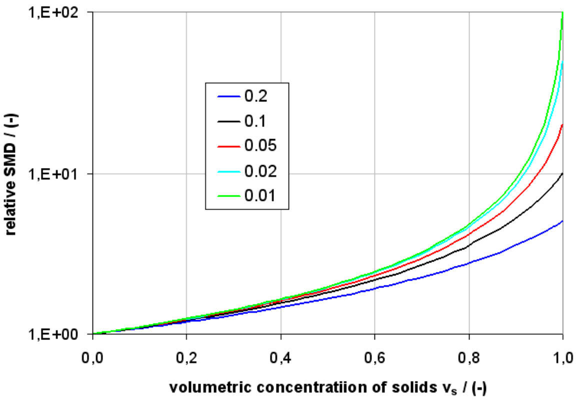

Fig. 6: Sauter mean diameter related to the size of liquid droplets for different v_s and R_d ratio.

If solid particles are large compared to droplets, the relative number of sprayed particles is very small (typically $n_s = 2 \cdot 10^{-6}$ for d_s = 1 mm, d_l = 50 µm, R_d = 0.02 and v_s = 20 %), see Fig. 5 and 6. Then the spray should be almost not affected by presence of solids and spray characteristics as D_{32} are similar to the pure liquid spray. It is in contrast with atomization of suspension containing smaller particles, where the final spray significantly differs from the spray of pure liquid [8].

CONCLUSIONS

Photographic spray documentation supported by simple calculations shows the atomization of suspensions with large particles is very similar to the spraying of pure liquid. This claim should be confirmed by direct measurement of droplet size in the future. Our newly designed atomizer with the “outside-in” gas injection configuration and exit orifice 3.5 mm in diameter was operated with suspension of LHO and solid particles in size up to 1.5 mm. All tests passed with no clogging problems or unsteady or other improper behaviour. It confirms a feasibility of effervescent atomizer for spraying of suspension containing large particles. Swirl of gas-suspension mixture prior to discharge significantly affects the spray cone angle. Spray cone angle of swirl atomizer is larger then spray cone angle of plane-orifice atomizer. The difference is distinct mainly at low GLR and diminishes with GLR rising.

KEYWORDS

Effervescent Atomizer, Suspensions, Waste Fuels, Spray Cone Half-Angle, Spray Structure

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NOMENCLATURE

Symbol	Quantity	SI Unit
D_{32}	Sauter mean diameter	µm
d	Particle diameter	µm
d_a	Aeration hole diameter	mm
d_c	Mixing chamber diameter	mm
d_o	Exit orifice diameter	mm
GLR	Gas to liquid ratio by mass	-
l_c	Length of the mixing chamber	mm
l_o	Length of the exit orifice	mm
N	Number of particles	-
n	Relative number of particles	-
p	Injection pressure	MPa
R_d	Ratio of d_s and d_l	-
V	Volume	m^3
v	Volumetric concentration (rel. volume)	-
Δl	Length of aeration area	mm
j	Particle index	
l	Liquid	
s	Solid particle	

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