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Development of an Effervescent Atomizer for Industrial Burners

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Effervescent Atomizer for Industrial Burners

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The present work is conducted with the aim of developing an effervescent atomizer for industrial burners that will generate a fine and steady spray in large turn-down ratio. The atomizer is fed with light heating oil (LHO) and uses air as an atomizing medium.

First, a basic classification is made of the published design concepts of effervescent atomizers investigated by different researchers. Three distinct types of such atomizers are recognized. A single-hole, plain-orifice atomizer with an “outside-in” gas injection configuration was chosen for this study. The basic geometric parameters that may significantly influence atomizer performance are described. An

experimental study of the effervescent atomizer was conducted to evaluate the influence of operational conditions and of several geometric parameters on the drop size in the spray. The Sauter mean diameter of drops was measured using a Phase/Doppler Particle Analyser. The study covers the size and number of aerator holes, their location, and the diameter of the mixing chamber. The influence of these parameters on the spray quality was evaluated at atomizing pressures of 0.1, 0.3 and 0.5 MPa and gas to liquid mass flow-rate ratios (GLR) of 2, 5 and 10 %.

The main goal of this work is to develop a new procedure for the design of effervescent atomizers. This procedure is based upon our experimental results and it is also supported by the findings of other authors. It allows for the determination of the key geometric parameters of the atomizer to achieve sprays of minimum mean drop size for defined values of liquid flow rate, air supply pressure and GLR. The article also studies the optimization of the exit orifice size and of other parameters, such as the size of the mixing chamber (internal diameter and length), and the number, size, and position of aeration holes.

1. Introduction

A method of atomization commonly referred to as „effervescent atomization” was developed in the late 1980s by Lefebvre and his colleagues,¹ though there are works mentioning similar concepts prior to Lefebvre.^{2,3} Effervescent atomizers belong to the class of twin-fluid atomizers with internal mixing. In the simplest form of the effervescent atomizer, gas is injected directly into a flowing liquid at low velocity upstream of the atomizer exit-orifice in such a way that a bubbly two-phase flow is created. As the liquid flows through the discharge orifice, it is transformed by the gas bubbles into thin shreds and ligaments. When the gas bubbles emerge from the nozzle at sufficient pressure drop, they expand so rapidly that the surrounding liquid is shattered into drops.

Effervescent atomizers are becoming more and more commonplace in numerous engineering applications where there is a need for liquid to be fragmented into drops. The major advantage of effervescent atomizers is their relative insensitivity to fuel physical properties, and ability to provide good atomization over a wide range of operational conditions even for low-grade fuels. The ability to vary both the operating pressure and the ratio of gas to liquid flow-rates, GLR, leads to large atomizer turn-down ratios. As the atomizing gas is utilized by an effervescent atomizer in a relatively efficient manner, a good atomization can be achieved using very small flow-rates of the gas. Another attractive feature that should be mentioned is its good atomization at low injection pressures. Furthermore, the effervescent atomizers can have a larger discharge orifice than conventional atomizers, which alleviates clogging problems and facilitates atomizer fabrication. It also predisposes this type of pneumatic atomizer for the atomization of suspensions and slurries.⁴⁻⁸

Despite its inherent simplicity, the effervescent atomizer allows a wide variety of design configurations.⁹ There is an extensive literature on the influence of the geometry of the liquid-air mixing system on the performance of effervescent atomizers. It has been shown that the optimization of the atomizer design can improve the spray characteristics. However, it is not possible to make generalisations based on these published results which were obtained using different atomizer concepts, for liquids of different physical properties (typically water) and at different operation conditions. We therefore decided to perform a new systematic study on one design configuration of the effervescent atomizer to examine the influence of the atomizer design on the spray performance at variable operation conditions with the use of light heating oil (LHO) as the atomized liquid. Considering the various design concepts investigated by different researchers, we chose the one best suited for the atomizer's application to an industrial LHO burner. A set of atomizers with variable geometry were fabricated and the corresponding spray produced was experimentally studied using a Phase/Doppler Particle Analyser. Several design parameters were modified: the size and number of aerator holes, their location and the diameter of the mixing chamber. The influence of these parameters on the spray performance was studied at atomizing pressures 0.1, 0.3 and 0.5 MPa and GLR of 2, 5 and 10 %, i.e. operation range

suitable for combustion applications. The measured data of drop size were utilized in our design procedure of the effervescent atomizer with the aim of producing an effervescent atomizer with a fine and steady spray in large turn-down ratio.

1.1. Effervescent Atomizer Configurations. Starting with the early papers,^{9,10} many different designs of effervescent atomizer have appeared. A basic classification of the single-hole plain-orifice effervescent atomizers, described in different works, is given below. The designs can be divided into three basic groups, see Figure 1.

Type A: In this configuration, the liquid flows usually through a central tube. Gas is introduced into the liquid by a set of small holes. This “outside-in” gas injection configuration enables a large liquid flow area which prevents clogging making it suitable for the atomization of slurries. This is probably the configuration that has been most frequently studied by researchers.^{4,7,8,10-22} The “inside-out” gas injection modification, where the inputs of gas and liquid are interchanged, has been less frequently studied and was investigated by Chin et al.⁹

Type B: Here, liquid flows through an annular port formed by the atomizer body and the aerator tube. Gas is introduced into the liquid by a set of small holes located on the aerator side and/or the aerator bottom. This “outside-in” modification has been mentioned in several papers.^{9,23-28} The difference between the “inside-out” and “outside-in” gas injection configuration of the B-type has been studied in Mostafa et al.²⁷

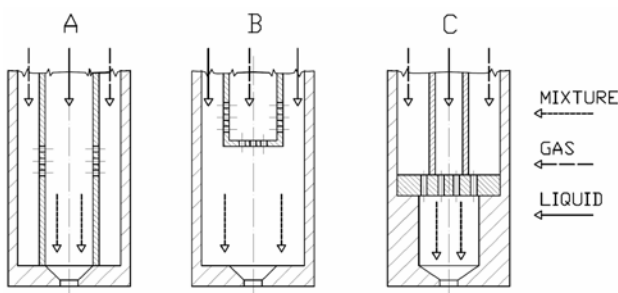


Figure 1. Simplified schemes of design configurations of the effervescent atomizer.

Type C: Both the fluids enter the mixing chamber separately. This configuration enables an independent control of the gas and liquid input velocity, direction and distribution. This version has been studied by Lee et al.,²⁹ Tamaki et al.³⁰ and Gong et al.³¹ If the liquid flows through an axial orifice and enters the chamber at large velocity, then mixing is prevented and other mechanisms become responsible for liquid disintegration. Such atomizers can be classified as common air-blast atomizers.³²

The use of different inserts^{20,27} or a static mixer⁸ inside the mixing chamber can modify and improve mixing and internal two-phase flow. The input of the gas can be modified by changing the position of aeration holes, their size and directions. The disintegration of pure liquids may be enhanced using perforated plates in front of the discharge orifice. The application of the so-called ligament-control inserts has been studied by Kuta et al.²⁶ and Sutherland et al.²⁴ Atomizers with annular discharge orifices^{9,33-34} or multi-hole atomizers^{10,13,20,35} may have a slightly different design and other more complicated and sophisticated designs may appear in the future, as, for example, in the case of combined atomizers.³⁶

In our research, we have used the A-type effervescent atomizer with an “outside-in” gas injection configuration as it seems to be the most promising for the atomization of LHO and for its possible utilization in the future for waste fuels.

1.2. Important Geometrical Parameters. The internal geometry of the effervescent atomizer is described according to the dimensions of its mixing chamber and the size and the shape of the discharge orifice (for individual parameters see section 2.1. Atomizer Description and Fig. 2 below). The main parameters of the mixing chamber studied in the past are: the size and number of aerator holes,^{9,12,27,37} the separation of aerator holes,⁹ the radial and axial inclination of aerator holes,^{12,27,30} the location of aerator holes relative to the final discharge orifice^{21,27} and the cross-section area of the mixing chamber.^{1,27,38}

The discharge orifice geometry is determined by the orifice diameter,^{1,4,10,13,21,27,38-40} the convergence angle at the inlet of the discharge orifice,⁹ the length to diameter ratio⁹ and the profile and shape of the exit orifice.^{9,18,24}

Based on an analysis of the above mentioned research works, we have focussed on four important geometrical parameters in the present work: the diameter and number of aerator holes, the location of the aerator holes relative to the final discharge orifice and the diameter of the mixing chamber.

2. Experimental Apparatus

The experimental equipment includes an effervescent atomizer, a cold test bench with fluid supply system and a Phase/Doppler Particle Analyzer.

2.1. Atomizer Description. A single-hole, plain-orifice atomizer of type A (Figure 1) was used. It consists of a cylindrical body in which an aerator tube is inserted. The aerator is connected to an exit nozzle. The liquid (oil) enters the central orifice of the aerator from the left side, while the air is injected into the liquid through a set of small holes in the aerator envelope. The two fluids form a two-phase mixture, flow downstream and exit the atomizer through a discharge orifice into the ambient atmosphere in the form of a spray.

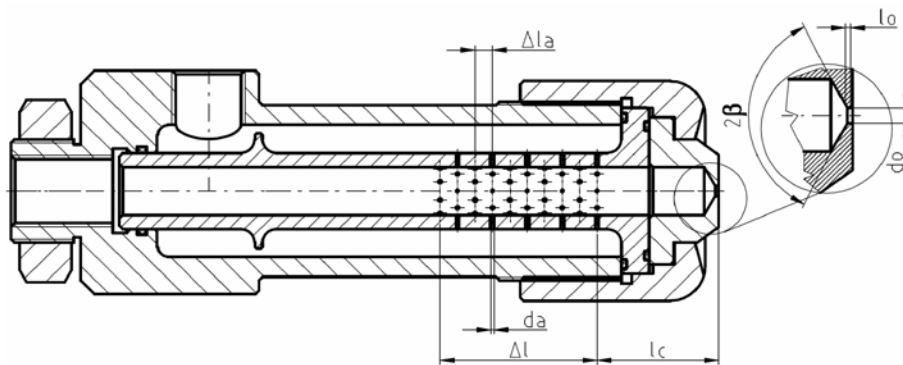


Figure 2. Schematic layout of the research atomizer.

The volume of the mixing chamber inside the aerator tube is given by the length downstream of the last row of air holes (l_c) and the internal diameter of the aerator tube (d_c). The length l_c and diameter d_c , together with the span length (Δl), diameter (d_a) and the number of aeration holes (N), have been varied in this study. Several atomizers were manufactured for testing; their dimensions are recorded in Table 1.

The exit orifice diameter, d_o , was fixed to 2.5 mm and length l_o to 0.7 mm. There was a conical junction with an apical angle of $2\beta = 120^\circ$ in front of the orifice.

2.2. Atomizer Operation. The atomizer was studied in the vertical downward position of the main axis. The physical properties of the atomized liquid, LHO, and the atomizing medium, air, are documented in Table 2. The atomizer was fed with LHO using air as the atomizing medium in the “outside-in” gas injection configuration, as can be seen in Figure 2. The air and oil supplies were controlled separately. The operational conditions of the twin-fluid atomizer with given geometry and fluids of defined physical properties can be basically described by two independent parameters. The oil flow rate was controlled by a gear pump, and the gauge pressure for the compressed air was set using a control valve. The air gauge pressure (18) (see Figure 3 below) measured right upstream the atomizer inlet corresponds to the atomizing pressure drop. Experiments were performed for several air gauge pressures and GLR values. The gauge pressures and volumetric flow rates of both media were measured and the GLR calculated. The temperatures of both fluids were kept at $20 \pm 2^\circ\text{C}$.

An Ubbelohde viscometer was employed to measure fluid viscosity (uncertainty value 7 %). We used the detach method to measure the surface tension (uncertainty value 5 %). The liquid index of refraction was measured using the Abbe model G refraction meter (Carl Zeiss, Jena) of which the refraction index uncertainty value is less than 1 %. The physical properties of water as the reference medium and of air are taken from the existing literature.

2.3. Test Bench. A schematic layout of the test rig is shown in Figure 3. It consists of a gear pump (14) that supplies LHO from a main fuel tank (16) through filters (15), control valves (9, 10) and flow meters into the atomizer (7). A chiller (11) ensures the constant oil temperature, hence its viscosity. The compressed air is impelled into the atomizer either from the central plant or from a two-stage compressor (1), depending on the required pressure through the air chamber (2), filters (4), control valve, check valve (5) and flow meters (6). Supply pressure and temperature of the atomizing air are closely measured by a pressure gauge (18) and a temperature sensor (17), and used for the density correction to estimate the corrected mass flow rate of air. The spray is collected in a vessel (12) and

beam with power up to 90 mW and horizontal polarization is split, using a transmitting optics 58N10, into 2 parallel beams 60 mm distant. The transmitting lens focal length is 500 mm, which results in a half-intersection angle between the beams of 3.43° . The frequency of one of the beams is shifted by 40 MHz. This configuration leads to a fringe separation of $4.3 \mu\text{m}$ and a probe volume of $0.4 \times 0.4 \times 6.7 \text{ mm}$. First-order refracted light is collected using a Dantec 57X10 receiving optics equipped with three photo-detectors. The focal length of the receiving lens is 500 mm and the scattering angle 69° . The setup enables us to measure the drop size up to $350 \mu\text{m}$. A Dantec 58N50 signal processor was set to measure velocity within a range of -25.8 to 128.9 m/s at bandwidth 36 MHz. The obtained data were evaluated using BSA Flow Software v2.1.

3. Influence of Operation Conditions on Spray Performance

As has been shown in a number of publications,^{10,12,19,20,41,42} drop size and velocity significantly depend on the input pressure drop and on GLR. The results of P/DPA measurement at an atomizing pressure of 0.2 MPa are documented in Figure 4. The radial profiles of D_{32} at the lowest GLR of 0.4 % are almost flat with an insignificant local maximum on the atomizer axis. This shape of D_{32} profiles is also documented by Li et al.¹³ and Kufferath et al.³² Profiles with a more distinct maximum on the atomizer axis have been noted by Lee et al.²⁹

Increase of GLR leads to decrease of D_{32} in the entire radial profile, but mainly near the spray axis. For GLR exceeding 0.6 %, the profiles tend to be inversely bell-shaped, with their minima on the spray axis. This change of D_{32} profiles with GLR can be related to the character of the internal two-phase flow: bubbly at small GLR, changing to slug, annular and, finally, to dispersed with the increase of the GLR. In the case of bubbly flow with small, well dispersed bubbles, the liquid is formed into thin ligaments at the discharge orifice, while, in the case of annular flow, the discharged liquid has the form of a sheath.^{16,43} The inversely bell-shaped radial size profiles were also documented by Lund et al.²³ and Mostafa et al.,²⁷ while other researchers^{29,44} have recorded a flat size profiles also at elevated GLR. To characterize atomization quality by a single parameter, we introduced an Integral Sauter Mean Diameter,

ID_{32} , which represents the whole spray at a certain cross-section perpendicular to the axis of the nozzle exit orifice. The simplified equation for the calculation of $ID_{32,i}$ at measurement position i , as derived in Appendix 1, reads:

$$ID_{32,i} = \frac{\sum_{i=2}^n (r_i \cdot D_{30,i}^3 \cdot f_i)}{\sum_{i=2}^n (r_i \cdot D_{20,i}^2 \cdot f_i)} \quad (1)$$

where $D_{30,i}$ and $D_{20,i}$ are the volumetric and surface diameters of drops measured at the radial position r_i . An ensemble of n drops is measured using P/DPA with drop arrival frequency f_i .

The ID_{32} calculated from data measured in radial profiles of D_{32} at a distance of 150 mm downstream the exit orifice is shown in Figure 5. Inequality of GLR range for particular pressure values was due to problems with optical access. The increase in GLR in regimes with pressure higher than 0.2 MPa led to the increased oil mist generation, and, on the other hand, the excessive decrease in GLR led to liquid splashing. Extensive range of GLR was used here only to show the general tendency of D_{32} with GLR. Practical atomizer operation conditions are limited by the maximal fluid pressure available but it is also desirable to keep GLR as low as possible for the sake of low energy consumption. The effervescent atomization efficiency decreases with the increase in GLR. The droplet velocity is going to be high at a very low liquid flow rate, which is not suitable for burner application. Our main research is focused on GLR in the range 2 – 10 %, useful in combustion applications, and which is a typical operation range of the effervescent atomizer.

Note that the term “effervescent atomization” is related to the operation of the atomizer in the bubbly or in the bubbly – slug two-phase flow regime inside the mixing chamber (see definition in Introduction chapter), where the atomizer benefits from good atomization at low gas consumption. This condition is for LHO fulfilled when GLR is lower than 5 % for chamber pressure 0.3 MPa. The effervescent atomizer is often used in regimes with GLR higher than 10 %, where the two-phase flow in the mixing chamber is different from the bubbly flow regime^{7,9,10,12,13,27}. The effervescent atomization is based on bubble formation and bubble rupture. The atomization process, in the case of annular or dispersed

internal two-phase flow (typically GLR higher than 15 %), relies on the aerodynamic shear force. We should use the term “internal mixing air assisted atomization” instead of the „effervescent atomization” to be correct in this case⁴⁵.

The ID_{32} decreases from 95 μm at GLR 0.4 % to 42 μm at GLR 100 % for a pressure of 0.2 MPa. The increase of the input gas pressure also leads to a finer spray. This dependence of atomization performance on atomizer operation conditions is in agreement with our earlier findings^{19,20} as well as with the results of other investigators.^{1,12,25}

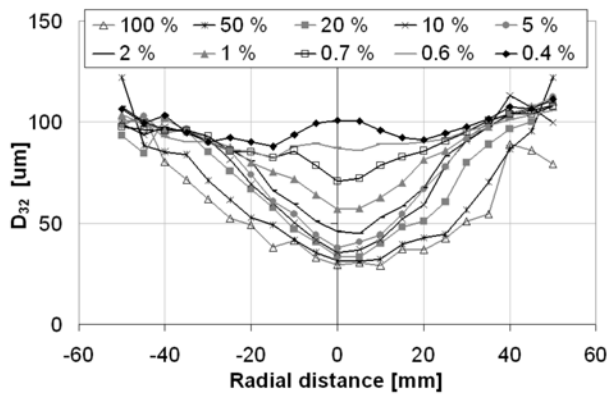


Figure 4. Radial profiles of D_{32} at $\Delta p = 0.2$ MPa and different GLRs, with axial distance from exit orifice 150 mm. Atomizer geometry: $d_o = 1.5$ mm, $r_{dc} = 4.4$, $r_{lc} = 3.3$, $r_n = 0.02$, $r_a = 6.5$.



Figure 5. Influence of GLR on ID_{32} . Atomizer geometry: $d_o = 1.5$ mm, $r_{dc} = 4.4$, $r_{lc} = 3.3$, $r_n = 0.02$, $r_a = 6.5$.

4. Influence of Atomizer Geometrical Parameters on Spray Performance

Based on published results, we have defined four geometrical parameters to study in this work: total area and diameter of aerator holes, diameter of the mixing chamber and location of the aerator holes relative to the final discharge orifice (see Figure 2 above). All the parameters are related to some characteristic atomizer dimension for atomizer scaling reasons. Radial profiles of drop size were measured using P/DPA at the axial distance 150 mm downstream of the final discharge orifice at air gauge pressures 0.1, 0.3 and 0.5 MPa and GLR 2, 5 and 10 %. For the sake of conciseness, only exemplary results were processed in the following plots. Mass flow rates of fuel and air corresponding to particular operating conditions are presented in Table 3 for all the atomizers tested. The axial distance of 150 mm was chosen for the P/DPA measurements for the following reasons. This distance is often used by the other researchers.^{10,24} Our preliminary results at different axial distances from the exit orifice (50, 100, 150 and 200 mm) indicate a fully developed spray (secondary breakup completed) at the distance of 150 mm. This is in accordance with the observations of Sher et al.¹² and Whitlow and Lefebvre.¹⁰ Very dense spray in the near-nozzle region causes namely multiple scattering effects and significant laser light attenuation when using optical measurement methods; small droplets are not seen by P/DPA and it leads to an overestimation of the resulting D_{32} value. Furthermore, the spray is not fully developed when too close to the nozzle orifice. Spray measurement at the distance larger than 150 mm from the nozzle exit is of limited value for combustion applications as the droplets would interact with the combustor flow-field and evaporate.

We employed atomizers E25-E28 (see Table 1) to study the impact of the diameter of the mixing chamber, d_c , on the drop size. The relative mixing chamber diameter can be defined by

$$r_{dc} = d_c / d_o . (2)$$

where d_o stands for the exit orifice diameter. The effect of the mixing chamber diameter is depicted in Figure 6a.

We varied the diameter of air injection holes, d_a , by applying E21-E24 atomizers. The number of the aerator holes, N , was also varied to keep the total aeration cross-section area constant. The influence of the relative area of a single aeration hole, r_n , on the spray, given as:

$$r_n = A_a / NA_a = \frac{\pi d_a^2}{4} / \frac{N \pi d_a^2}{4} = 1/N, \quad (3)$$

is evaluated in Figure 6b.

Atomizers E30, E33, E36 and E38 were used to investigate the influence of the aeration cross-section area on the atomization process. The cross section area was modified by a variation of the number of aerator holes with their diameter maintained constant. The relation between ID_{32} and the relative aeration cross-section area, r_a , is shown in Figure 6c. r_a is a ratio of the aeration area and the area of the final discharge orifice:

$$r_a = NA_a / A_o = N(d_a / d_o)^2. \quad (4)$$

The location of aeration holes relative to the final discharge orifice described by the length l_c defines the relative mixing distance:

$$r_{lc} = l_c / d_c = l_c / (r_{ac} d_o). \quad (5)$$

The parameter r_{lc} was studied using atomizers having one, three and five lines of aeration holes. The number of the holes in each line was 8 for all the atomizers. The behaviour of atomizers E29-E31 having one line of aeration holes is documented in Figure 6d, atomizers E32-E34 having three lines of aeration holes in Figure 6e and atomizers E35-E37 having five lines of aeration holes in Figure 6f. Comments and analysis of all the results shown in Figure 6 are made in the next chapter.

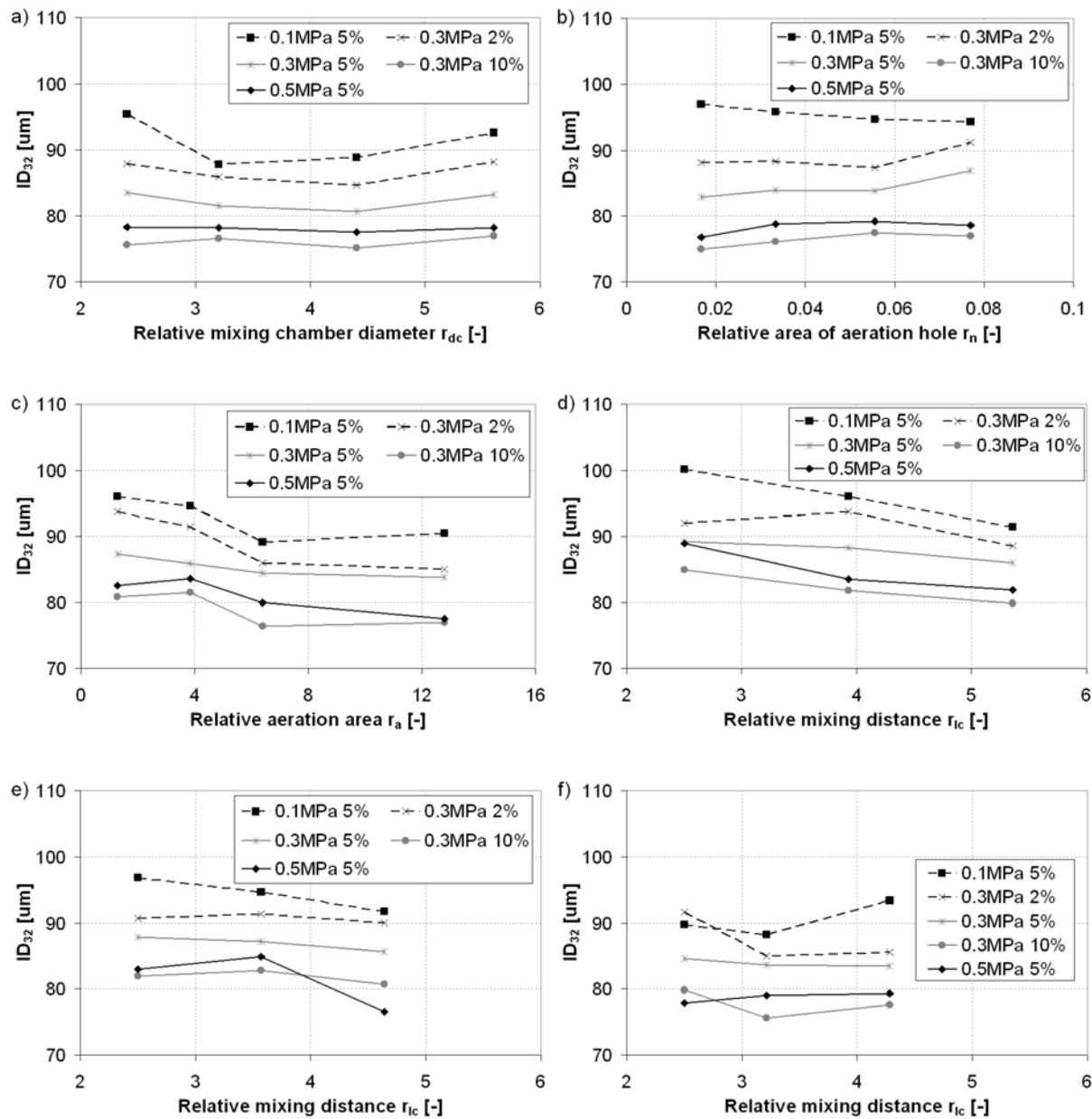


Figure 6. Integral Sauter mean diameter measured in spray at a distance of 150 mm from the exit orifice for different operation pressures and GLR's. The plots depict the influence of different geometric parameters: a) relative mixing chamber diameter (atomizers E25-E28); b) relative area of aeration hole (atomizers E21-E24); c) relative aeration area (atomizers E30, E33, E36 and E38); relative mixing distance for d) atomizers E29-E31 with one line of aeration holes, e) atomizers E32-E34 with three lines of aeration holes and f) atomizers E35-E37 with five lines of aeration holes.

5. Atomizer Design Procedure

When designing an effervescent atomizer some key parameters are usually known at the beginning. They include the liquid and gas properties, the liquid flow rate, and the maximum available supply pressures of air and liquid. The GLR may or may not be known. If a desired mean drop size is specified, then, using Figure 5, an optimum GLR can be found to ensure the spray quality. At this stage of the design we neglect the influence of the atomizer design on the atomizer performance and consider it less significant than the effect of operation conditions.

5.1. Discharge Orifice. The geometry of the plain discharge orifice is given by a length/diameter ratio of the throat section, l_o/d_o , and the angle of the flow convergence downstream of the mixing chamber 2β . The convergence angle has little effect on the spray mean drop size, provided it is less than around 120° .⁹ Mostafa et al.²⁷ also found a slight effect of the convergence angle on the spray up to $2\beta = 140^\circ$ but an abrupt increase in drop size if a nozzle with a hole at the centre of a simple plate ($2\beta = 180^\circ$) was used. A value for 2β of $90^\circ - 120^\circ$ is recommended because it gives good flow characteristics using a relatively short length of the exit orifice. Of more importance to atomization is the length/diameter ratio of the final discharge orifice. Reduction in l_o/d_o yields improvements in atomization, so this ratio should be as small as possible with respect to manufacturing limitations.⁹ The effect of the diameter of the final discharge orifice on the drop size has been examined by several investigators.^{1,4,13,21,27,37,46} In all the cases, it has been found that the differences in the drop size as generated by nozzles with different final discharge orifice diameters were always quite small. The performance of multi-hole atomizers is the same as those of single-hole atomizers for the same l_o/d_o ratio.^{10,13} These findings facilitate the design of multi-hole atomizers; the spray shape and spray cone angle can be simply varied to comply with the atomizer application. The discharge orifice size determines the atomized liquid mass flow rate:

$$\dot{m}_l = C_D A_o \sqrt{2\Delta p \rho_l} \cdot (6)$$

The discharge coefficient of the exit orifice C_D is influenced by the nozzle size and geometry, atomizer operation conditions and physical properties of the atomizing gas and atomized liquid. Based on published works and our tests of more than thirty plain-orifice atomizers, the following equation for the discharge coefficient was found:

$$C_D = C_{D1}C_{D2}C_{D3} \quad (7)$$

where C_{D1} reflects the physical properties of the atomized liquid by the equation⁹

$$C_{D1} = (\mu')^{0.04}(\sigma')^{0.02} \quad (8)$$

where μ' is the liquid/water viscosity ratio and σ' the liquid/water surface tension ratio. For particular data, see Table 2 above. The second term, C_{D2} , describes the effect of the nozzle geometry:

$$C_{D2} = 0.62 \left(\frac{l_o}{d_o} \sin(2\beta)^{0.5} \right)^{-0.11}. \quad (9)$$

The equation is valid for β smaller than 90° . And C_{D3} represents the atomizer operation conditions:

$$C_{D3} = \frac{G}{\sqrt{2\Delta p \rho_l}} \frac{1}{(1 + GLR)}. \quad (10)$$

The total mass velocity G is calculated by combining the Homogeneous Frozen Flow Model (HFFM) and the Separated Flow Model (SFM):⁴⁷

$$G = 0.5(G_{HFFM} + G_{SFM}), \quad (11)$$

$$G_{HFFM} = \frac{\left[\frac{2p_1}{\alpha_1 v_1} \left[\left(\frac{1-\alpha_1}{\alpha_1} \right) (1-\pi) + \left(\frac{k}{k-1} \right) (1-\pi^{(k-1)/k}) \right] \right]^{1/2}}{\pi^{-1/k} + \left(\frac{1-\alpha_1}{\alpha_1} \right)} \quad (12)$$

and:

$$G_{SFM} = (GLR + 1) \sqrt{p_1} \left[\frac{1}{\sqrt{2(1-\pi)\rho_l}} + \frac{GLR}{\pi^{\frac{-1}{k}} \sqrt{2\rho_{g1} \frac{k}{k-1} (1-\pi^{(k-1)/k})}} \right]^{-1} \quad (13)$$

where α is the gas volume fraction:

$$\alpha = \frac{\dot{V}_g}{\dot{V}_g + \dot{V}_l} \quad (14)$$

and π is the pressure ratio:

$$\pi = p_2/p_1. \quad (15)$$

The solution of Eqs. (12) and (13) can be split into two intervals: $\pi \in \langle \pi_c, 1 \rangle$ and $\pi \in \langle 0, \pi_c \rangle$. Within the first interval, the equations are solved directly, in the second one, the value π in Eqs. (32a) and (32b) is replaced by the critical pressure ratio, π_c . π_c is a ratio at which both the functions, Eqs. (12) and (13) respectively, reach their maxima. Searching for the critical value of π_c in the Eq. (12) is done numerically. Critical value of π_c in the Eq. (13) is:

$$\pi_c = \left(\frac{2}{k+1} \right)^{k/(k-1)}. \quad (16)$$

For detailed information about the derivation of both the flow models and a comparison of the calculated discharge coefficient with experimental data see Appendix 2. The proposed model gives a better prediction of the nozzle discharge coefficient, C_D , than the empirical correlation⁹ and is also superior to calculations of Chen et al.⁴⁸

Knowledge of liquid physical properties, atomizer operation conditions and preliminary values of the nozzle length-diameter ratio and the convergence angle 2β enables us to calculate the discharge orifice diameter that would give the desired liquid flow rate using Eqs. (6)-(13).

5.2. Gas Injection Holes. The ratio of the aeration area to the area of the final discharge orifice, r_a , (Eq. (4)) governs the corresponding ratio of the gas velocity through air injection holes to the gas velocity through the discharge orifice. Our experiments (Figure 6c) show that relative aeration area of about 8 to 12 gives the smallest drop size independently of pressure and GLR. Large aeration area increases the contact area between the gas and liquid and hence it improves mixing. Mixture composed of thin liquid ligaments and small air volumes at the exit orifice is a prerequisite to the good utilization of the atomizing air to shatter liquid volumes into small droplets.

The size of aerator holes slightly influences the atomization quality as illustrated in Figure 6b. At pressure 0.1 MPa and GLR 5 %, the ID_{32} decreases with the enlargement of the relative area of the aeration hole, r_n . Similar behaviour was encountered also at regimes with the pressure set to 0.1 MPa and GLR to 2 %, and with the pressure set to 0.1 MPa and GLR to 10 %. At higher pressures between 0.3 and 0.5 MPa, the ID_{32} shows opposite behaviour for the whole range of GLR tested. Atomization

pressure (pressure drop between the mixing chamber and ambient air) influences significantly discharge velocity and fluid flow rates (see Table 3). Tiny air bubbles formed by small aeration holes have low momentum and limited capability of penetration into liquid and work well at low flow rates while larger bubbles mix up with the liquid more easily also at large flow rates. The design of the aerator hole diameter hence depends on the assumed range of operation pressures. Generally, the influence of the aerator holes diameter on the atomization performance is relatively small compared to other inspected factors.

5.3. Mixing Chamber Size. The cross-section of the mixing chamber influences the character of two-phase flow and pressure loss downstream of the mixing chamber. Figure 7 illustrates a possible two-phase flow patterns in case of a horizontal flow using a modified Baker's map for fully developed horizontal two-phase flow with transformed coordinates. The calculation procedure for X and Y coordinates is beyond the scope of this paper and can be found elsewhere.^{43,49} The data in Figure 7 is calculated for an atomizer with mixture of LHO and air as the working media at the inlet pressure of 0.2 MPa and GLR 10 % by variation of the diameter of the mixing chamber. Note that relative mixing distance, r_{lc} , studied here, reaches values 2.5 – 16.4, as indicated in Table 1. The length from the inlet gas holes to the exit orifice does not allow the flow to fully develop thus the applicability of the published flow regime map is limited in this case⁴³. It is used here to give the idea of what happens inside the atomizer. The two-phase flow pattern changes from bubbly-froth, in case of relative diameter $r_{dc} = d_c/d_o$ of 2.5, to slug and almost to stratified ($r_{dc} = 8$). Too large r_{dc} results in low pressure loss but also an improper two-phase flow pattern that leads to slug flow and, in the case of horizontal flow, to vertical separation of liquid and gas. It results in an uneven distribution of liquid into the individual orifices of multi-hole atomizers.²⁰ The cross section of the mixing chamber and resulting two-phase flow pattern also influence the atomization process. Figure 6a shows the significant effect of the relative mixing chamber diameter r_{dc} , at low pressure, where the smallest ID_{32} is found for r_{dc} of about 3 - 4. For high pressure and GLR, the dependence of ID_{32} on the chamber diameter almost disappears.

The increase in pressure leads to shift of the operation point right and upwards, and the increase in GLR leads to the shift left and upwards as indicated by gray arrows in the two-phase flow diagram in Figure 7. The two-phase flow regime for operation at pressure 0.2 MPa and GLR 2 % is near plug-bubbly transition for $r_{dc} = 3 - 4$ and moves toward frothy flow with the increase in r_{dc} or towards plug flow with the decrease in r_{dc} . Two-phase flow pattern transitions caused by the r_{dc} variation in case of atomizer operation at low pressure and low GLR influence a mixture at the atomizer exit more strongly than in case of atomizer operation at high pressure and high GLR.

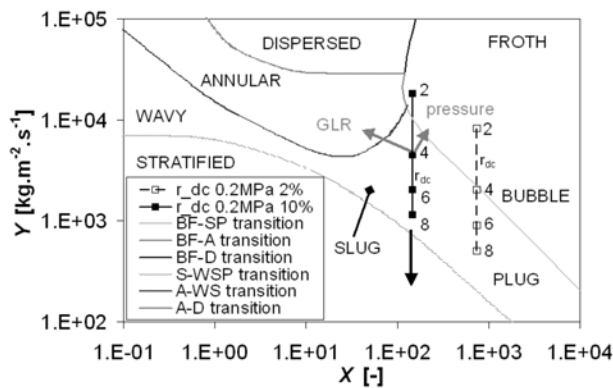


Figure 7. Modified Baker's map for horizontal two-phase flow with transformed coordinates⁴⁹ showing the marked influence of the relative mixing chamber diameter r_{dc} , on the two-phase flow pattern for regimes $p = 0.2$ MPa & GLR = 2 % and $p = 0.2$ MPa & GLR = 10 %. The black arrow shows an increase of r_{dc} . Gray arrows show the influence of the atomizer inlet pressure and GLR respectively. The atomizer is operating with LHO, $d_o = 2.5$ mm.

The distance between the last set of aeration holes and the final discharge orifice (mixing chamber length), l_c , provides the free travelling length of the two-phase mixture. Both the splitting of larger volumes of segregated phases with homogenization of the mixture and bubble-merging are possible depending on the conditions of the two-phase flow as indicated in our previous study.²⁰ The results of Sher et al.¹² show an optimum distance depending on GLR, while others^{21, 27} found that a large mixing length produces a small mean drop size. Our results (Figure 6d) exhibit a relatively strong correlation

between the location of aeration holes, r_{lc} , and the mean drop size in case of small aeration area while using a single row of aeration holes; the minimum drop size is acquired at the large mixing length. The influence of r_{lc} reduces when the number of aeration lines is 3 (Figure 6e). Very small influence of r_{lc} with no definite trend in the ID_{32} variation is shown when 5 line aerators are considered (Figure 6f). It indicates that the two-phase mixture acquired using such a large aeration area is relatively well mixed and it does not develop significantly during its transport to the exit orifice. The Figures 6d-f also show that the larger the aeration area, the smaller drop size (3 line aerators have the smallest aeration area while 5 line aerators have the largest). The large aeration area produces great gas-liquid interface and enables good mixing which is important for efficient utilization of the atomizing air. Note that a low number of aeration holes, at low pressure and low GLR, especially caused unsteady spray behaviour. This phenomenon was more pronounced at large relative distances, r_{lc} . The phenomenon of effervescent spray unsteadiness is described in more detail by Jedelsky et al.⁵⁰ A comparison of results for all the atomizers E29-E37 (Fig. 6d-f) leads to the conclusion that the best results are acquired with a great number of aeration holes and a relative mixing chamber length, r_{lc} , of about 3.5. The final determination of the optimum mixing chamber diameter and length depends on the required atomization quality, pressure losses and assembly requirements.

Using Fig. 6a-f, we conclude the influence of the atomizer geometry on the spray droplet size is reasonable. The maximum variability in ID_{32} amongst all the atomizers tested is about 15 μm within the whole range of operation conditions used in the tests. The largest variation is seen in case of air gauge pressure 0.2 MPa and GLR 2 %; the variation decreases with both the pressure and GLR. It indicates larger impact of the atomizer design on bubbly and slug internal two-phase flow patterns existing at low pressure and low GLR than on annular and frothy patterns present at higher pressure and/or higher GLR.

6. Conclusion

Of the three different design concepts of an effervescent atomizer identified, the A-type with “outside-in” gas injection configuration was chosen for the development of an atomizer to spray LHO using an industrial burner. Several important parameters of atomizer internal geometry have been specified.

The experimental part of our work focused on a study of the influence of the operation conditions and the atomizer geometry on the drop size in the spray. The results document the variation in drop size, represented by the Sauter mean diameter, according to the radial position in the spray. This variation leads us to a definition of the integral value of the Sauter mean diameter if the atomization performance is to be measured by a single parameter. The operation conditions of the atomizer are defined by the input pressure and by GLR. The increase of GLR significantly reduces the spray drop size. An increase of the operation pressure also leads to finer sprays, but its influence is rather weak. Four geometric parameters have been studied experimentally: the size and number of the aerator holes, their location and the diameter of the mixing chamber. Our evaluation of the integral Sauter mean diameter on a set of nozzles with modified design parameters has led to several conclusions:

- The influence of the atomizer design on its performance is moderate.
- Optimum results can be acquired with the use of a mixing chamber diameter about 4 times the exit orifice diameter
- A larger number of aeration holes with smaller diameter leads to a decrease in the drop size.

The study results in a new design procedure to determine the key geometric parameters of an atomizer aimed at achieving sprays of minimum mean drop size for given values of liquid flow rate, air supply pressure and GLR. The procedure enables an optimisation of all the main design parameters: the exit orifice size, the size of the mixing chamber (internal diameter and length), and the number, size and position of the aeration holes.

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Supporting Information Available

Appendix 1: derivation of the Integral Sauter Mean Diameter.

Appendix 2: derivation of both the HFFM and SFM flow models in detail, comparison of the calculated discharge coefficient with experimental data.

This information is available free of charge via the Internet at <http://pubs.acs.org/>.

Nomenclature

A_a = area of a single air injection hole (m^2 , mm^2)

A_o = area of final discharge orifice (m^2 , mm^2)

C_d = discharge coefficient

$D_{20,i}$ = surface diameter of drops measured in the measurement position i (μm)

$D_{30,i}$ = volumetric diameter of drops measured in the measurement position i (μm)

D_{32} = Sauter Mean Diameter (μm)

d_a = diameter of air injection holes (mm)

d_c = diameter of the mixing chamber (mm)

d_o = diameter of the final discharge orifice (mm)

f_i = drop arrival frequency (Hz)

G = mass velocity ($\text{kg}/\text{m}^2 \text{ s}$)

GLR = gas-to-liquid mass flow-rate ratio (%)

i = index number

ID_{32} = Integral Sauter Mean Diameter (μm)

k = gas isentropic exponent

l_c = length downstream of the last row of air holes (mm)

l_o = length the final discharge orifice (mm)

\dot{m} = mass flow rate (kg/s, g/s)

n_r = index of refraction

n = number of drops measured by P/DPA

N = number of aeration holes

p = pressure (Pa)

r_a = relative aeration cross-section area as defined in Eq. (4)

r_{dc} = relative mixing chamber diameter as defined in Eq. (2)

r_i = radial distance in the measurement position i (mm)

r_{lc} = relative mixing distance as defined in Eq. (5)

r_n = relative area of single aeration hole as defined in Eq. (3)

V = volume (m³)

v = specific volume (m³/kg)

Greek Symbols

α = gas volume fraction (void fraction) as defined in Eq. (14)

β = half-angle of the flow convergence downstream of the mixing chamber (deg)

Δl = span length between the first and the last set of aeration holes (mm)

Δp = pressure differential between the mixing chamber and ambient air (Pa, MPa)

Δp_{gl} = pressure differential between gas and liquid at atomizer inlet (kPa)

π = pressure ratio as defined in Eq. (15)

μ = dynamic viscosity (N s/m²)

μ' = liquid/water dynamic viscosity ratio

ρ = density (kg/m³)

σ = surface tension (N/m)

σ' = liquid/water surface tension ratio

Subscripts

1 = in the atomizer mixing chamber

2 = at the atomizer exit (ambient air conditions)

a = air

g = atomizing gas, usually air

i = measurement position

l = atomized liquid

w = water

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Tables

Table 1. Dimensions of Tested Atomizers

At. ^a	l_c (mm)	Δl (mm)	d_c (mm)	d_a (mm)	N (-)	r_a (-)	r_N (-)	r_{dc} (-)	r_{lc} (-)
E21	90	30	5.5	0.7	60	4.70	0.017	2.2	16.4
E22	85	30	5.5	1.0	30	4.80	0.033	2.2	15.5
E23	85	25	5.5	1.3	18	4.87	0.056	2.2	15.5
E24	90	25	5.5	1.5	13	4.68	0.077	2.2	16.4
E25	85	30	5.5	1.0	30	4.80	0.033	2.2	15.5
E26	85	30	8.0	1.0	30	4.80	0.033	3.2	10.6
E27	85	25	11.0	1.0	30	4.80	0.033	4.4	7.7
E28	85	40	14.0	1.0	30	4.80	0.033	5.6	6.1
E29	75	0	14.0	1.0	8	1.28	0.125	5.6	5.4
E30	55	0	14.0	1.0	8	1.28	0.125	5.6	3.9
E31	35	0	14.0	1.0	8	1.28	0.125	5.6	2.5
E32	65	10	14.0	1.0	24	3.84	0.042	5.6	4.6
E33	50	10	14.0	1.0	24	3.84	0.042	5.6	3.6
E34	35	10	14.0	1.0	24	3.84	0.042	5.6	2.5
E35	65	20	14.0	1.0	40	6.40	0.025	5.6	4.6
E36	45	20	14.0	1.0	40	6.40	0.025	5.6	3.2
E37	35	20	14.0	1.0	40	6.40	0.025	5.6	2.5
E38	35	40	14.0	1.0	80	12.80	0.013	5.6	2.5

^a Atomizer label

Table 2. Physical Properties of Fluids at Room Temperature

Fluid	μ (kg/m·s)	σ (kg/s ²)	n_r (-)	ρ (kg/m ³)
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LHO	0.0185	0.0297	1.488	874
Air	1.82×10^{-5}	-	1.001	1.23^b
Water ^a	0.0010	0.0727	1.333	1000

^a reference medium

^b normal conditions

Table 3. Operation Conditions of Tested Atomizers

Δp (MPa)	0.1			0.3			0.3			0.3			0.5		
GLR (%)	5			2			5			10			5		
At. ^a	Δp_{gl}	m_g	m_l	Δp_{gl}	m_g	m_l	Δp_{gl}	m_g	m_l	Δp_{gl}	m_g	m_l	Δp_{gl}	m_g	m_l
	(kPa)	(g/s)	(g/s)	(kPa)	(g/s)	(g/s)	(kPa)	(g/s)	(g/s)	(kPa)	(g/s)	(g/s)	(kPa)	(g/s)	(g/s)
E21	4.6	0.82	16.0	9.2	0.93	45.5	7.1	1.57	31.4	5.0	2.09	21.1	9.9	2.27	45.1
E22	5.3	0.83	16.4	11.1	0.91	45.7	7.5	1.56	31.5	3.4	2.12	21.0	10.8	2.27	45.0
E23	4.5	0.82	16.7	9.4	0.93	46.3	7.1	1.57	31.4	5.0	2.10	21.2	10.1	2.24	45.6
E24	5.3	0.84	16.7	10.5	0.89	46.0	7.8	1.57	31.7	5.5	2.12	21.2	9.8	2.26	45.6
E25	5.1	0.83	16.5	10.5	0.92	46.0	6.6	1.57	31.5	4.2	2.11	21.2	10.6	2.26	45.4
E26	2.0	0.79	15.7	7.9	0.95	47.1	4.7	1.58	31.8	2.0	2.14	21.6	6.3	2.30	46.2
E27	2.4	0.85	16.7	5.3	0.94	46.4	2.8	1.58	31.7	1.5	2.13	21.4	4.5	2.25	45.3
E28	2.1	0.88	17.3	5.5	0.96	47.9	3.4	1.61	32.4	2.1	2.18	21.9	4.4	2.20	44.3
E29	0.9	0.84	16.5	5.9	0.94	47.4	1.4	1.60	31.7	-3.3	2.18	21.7	1.4	2.27	45.7
E30	0.8	0.86	16.8	6.5	0.95	46.4	1.7	1.55	31.6	-2.9	2.11	21.3	2.6	2.22	45.1
E31	1.6	0.83	16.1	8.6	0.93	46.4	2.1	1.55	31.6	-1.7	2.12	21.3	2.7	2.20	44.4
E32	1.5	0.85	16.8	6.9	0.93	47.4	2.5	1.58	32.3	-1.4	2.14	21.2	3.5	2.28	46.2
E33	1.4	0.84	16.7	7.1	0.93	47.5	2.7	1.59	32.0	-1.4	2.13	21.3	3.3	2.28	45.8
E34	0.8	0.85	16.6	7.3	0.93	47.2	2.3	1.59	32.0	-1.7	2.14	21.4	3.1	2.28	45.6
E35	2.2	0.87	17.5	8.6	0.94	46.4	4.1	1.60	32.0	3.0	2.17	21.6	6.4	2.23	45.7
E36	2.0	0.88	17.4	8.5	0.95	46.7	4.8	1.60	31.9	2.1	2.15	21.6	6.4	2.24	45.4

E37	2.9	0.88	17.6	8.4	0.95	47.0	6.9	1.60	32.0	4.0	2.15	21.8	8.3	2.25	45.8
E38	3.1	0.84	16.6	9.4	0.95	46.8	6.5	1.59	31.8	4.2	2.16	21.8	8.3	2.27	44.9

^a Atomizer label