Energy equilibrium analysis in the effervescent atomization

Duan, Runze; Feng, Ziwei; Duan, Hongbin; Qu, Huiru; Tian, Liting; Jia, Wenqi; Baleta, Jakov; Wang, Enyu; Liu, Liansheng; Tian, Liang

Research Article

Runze Duan, Ziwei Feng, Hongbin Duan, Huiru Qu, Liting Tian, Wenqi Jia, Jakov Baleta, Enyu Wang*, Liansheng Liu*, and Liang Tian

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Abstract: In this paper, the flow characteristics and energy equilibrium analysis of the effervescent atomization had been investigated theoretically and experimentally. The effect of the gas–liquid rate (GLR from 0.04 to 0.15) on the atomization stability was revealed. When the GLR was small, the atomization was unstable. The atomization was gradually stable with an increase in the GLR. The optimal atomization region can be obtained. The Sauter mean diameter (SMD) of the droplets was measured by the phase Doppler analyzer. The SMD decreases with an increase in the GLR. The energy equilibrium analysis was investigated for the swirl atomizer theoretically and experimentally. The results show that the energy dissipation terms are mainly compressed gas expansion, liquid viscosity dissipation, and resistance losses. However, the ratio of the spray kinetic energy and the surface tension energy to the total energy is small.

Keywords: effervescent atomization, energy dissipation analysis, Sauter mean diameter, swirl atomizer, droplets velocity, phase Doppler analyzer

*** Corresponding author: Enyu Wang,** School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, 300401, China; Hebei Key Laboratory of Thermal Science and Energy Clean Utilization, Tianjin 300401, China, e-mail: wey@hebut.edu.cn, tel: +86-022-6043-8208
*** Corresponding author: Liansheng Liu,** School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, 300401, China; Hebei Key Laboratory of Thermal Science and Energy Clean Utilization, Tianjin 300401, China, e-mail: liuliansheng@hebut.edu.cn, tel: +86-022-6043-8208
Runze Duan: School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, 300401, China; Hebei Key Laboratory of Thermal Science and Energy Clean Utilization, Tianjin 300401, China
Ziwei Feng: School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, 300401, China
Hongbin Duan: Shanxi Jinnan iron and Steel Group Co., Ltd, Shanxi, 043400, China
Huiru Qu: School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, 300401, China; Tianjin Hongya Energy Conservation Co., Ltd, Tianjin 300401, China
Liting Tian: School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, 300401, China; Hebei Key Laboratory of Thermal Science and Energy Clean Utilization, Tianjin 300401, China
Wenqi Jia: School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, 300401, China
Jakov Baleta: Faculty of Metallurgy, University of Zagreb, Sisak, 44000, Croatia
Liang Tian: School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, 300401, China; Hebei Key Laboratory of Thermal Science and Energy Clean Utilization, Tianjin 300401, China

1 Introduction

The effervescent atomization has some advantages such as high atomization quality, low pressure, energy-saving, simple, and reliable. Effervescent atomization technique has been already widely used in many industrial applications, such as liquid fuel combustion, spray cooling, spray irrigation, water mist for fire suppression, medical treatment, and surface spray treatment [1–5]. The main purpose of the atomization is to make the liquid into fragments or small droplets [6–8]. The atomization process needs to consume a lot of energy on the inside and outside of the effervescent atomizer [9–11]. The effects of energy consumption must be considered when an atomizer is designed and chosen. Hence, it is necessary to investigate energy transfer in the effervescent atomization process.

The process of effervescent atomization has been investigated by Lefebvre et al. in the 1980s [12–14]. Using injecting gas into a liquid, bubble flow is formed in the internal-mixing chamber of the atomizer. The effervescent atomization is the result of liquid and gas interaction. When the liquid and gas shear force is greater than the fluid viscous forces and surface tension, the liquid will be deformed and broken into small droplets. When the gas and the droplets continue the interaction, the droplets will be further broken into smaller liquid particles, then the atomization is achieved.

The mean spray droplet size (typically Sauter mean diameter [SMD]), spray cone angle, and the discharge coefficient are the most important performance parameters to atomizer designers. Wade et al. [15] and Wang et al. [16] experimentally investigated the spray characteristics of an effervescent atomizer operating in the MPa injection pressure range. The atomization reason is that the high gas–liquid velocity difference enhances the shear effect. Satapathy et al. [17] continued the work of Wade et al. They found that the ambient gas density is a small influence on SMD. Sovani et al. [18] reinforced the conclusions of Wade et al. and Satapathy et al. They found that the efficiency of the effervescent atomizers is substantially higher than the efficiencies of the conventional twin-fluid atomizers. The same conclusion is obtained by Bayvel and Orzechowski [19]. They indicate that the atomization efficiency of the effervescent atomization is higher than that of other atomizers. The spray quality improvement of the effervescent atomization demands less energy. Karnawat and Kushari [20] thought the spray cone angle is dependent on the GLR. Sovani et al. [21] noted the spray cone angle is widened with an increase in the injection pressure. Chen and Lefebvre [22] found that the spray cone angle increases with a decrease in the liquid viscosity and surface tension. Ochowiak [23] investigated the effect of the discharge coefficient of the effervescent atomizer on the effervescent atomization. The conclusions are that the atomizer construction (mixing chamber and outlet orifice) is very important to discharge coefficient.

All the literature mentioned earlier focuses mainly on the performance parameters of atomization. However, energy consumption in the atomization process is also important to design atomizers and improve atomization quality. Lefebvre et al. [24,25] investigated the energy consideration in twin-fluid atomization. The results are that the ratio of the energy required for atomization to the kinetic energy of the air is a main factor for the atomization. Jedelsky and Jicha [26] systematically investigated the energy conversion process of the effervescent atomization by the experiment. The conclusions are that most of the input energy is spent on the gas expansion work, the air entrainment process, and losses related to the two-phase flow and the discharge. However, viscosity dissipation is not considered. The viscosity has a very important influence on the atomization process and atomization energy consumption.

In this paper, first, the effect of gas–liquid rate (GLR) on the atomization stability is investigated. Second, the effect of two atomizer configuration on the atomization characteristics (velocity and SMD of droplets) is studied. On this basis, the energy equilibrium analysis is investigated for the swirl atomizer in detail. It is hoped that the present work can provide a good scheme for designing effervescent atomizer.

2 Experimental system

The experimental system of the effervescent atomization is illustrated in Figure 1. The pressure of the gas and liquid which was provided by the gas compressor was measured by the pressure gages. The flow rate of the fluid was measured by the mass flow meter, and the gas rate was obtained by the volume flow meter. The gas and liquid are mixed in the atomizer and then flow downstream to the exit orifice. The velocity and size of the droplet were measured by the phase Doppler analyzer (PDA). The spray temperature field was measured by the thermal infrared imager, and the spray stability was analyzed by the high-speed video.

Before entering the atomizer, the pressure of the liquid and gas was up to 0.3 MPa. The structure of the swirl atomizer is shown in Figure 2. The diameter of the exit orifice was D = 1.0 mm. The diameter of the mixing chamber was D_c = 10 mm. The degrees of mixing and energy interchange between air and water were different in the mixing chamber, then sprayed from the atomizer exit.

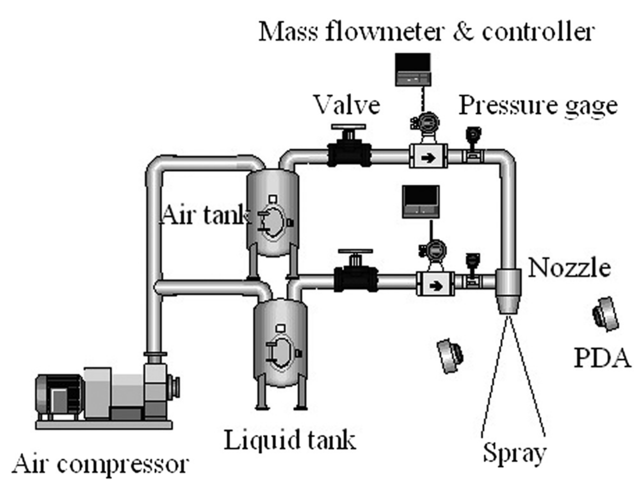

Figure 1: Experimental system.

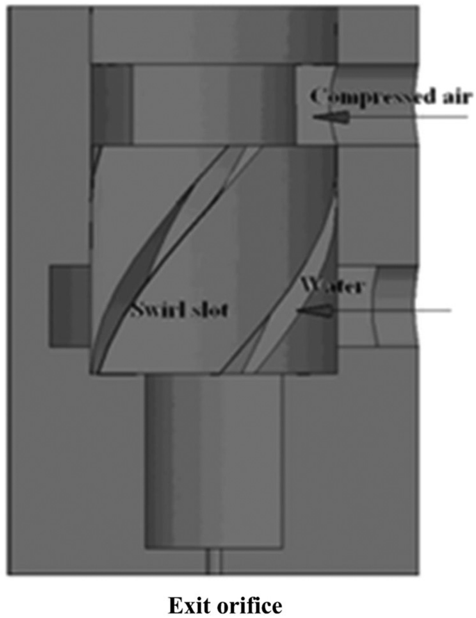

Figure 2: Structure of the swirl atomizers.

3 Results and discussion

3.1 Characteristic of the atomization in the effervescent atomizer

The characteristic of the atomization in the effervescent atomizer is shown in Figure 3. The pressure of the gas and liquid was changed from 0.26 to 0.32 MPa. The liquid mass flow rate decreases with an increase in the GLR, as shown in Figure 3. The physical mechanisms are revealed as follows: when the GLR is small, the amount of liquid is relatively much more than that of air. The liquid is sprayed from the exit orifice to the stationary atmosphere environment; the restriction of the atomizer wall for the liquid is disappeared. Due to the interaction of gas and liquid, the atomization becomes unstable in the gas–liquid boundary layer. The atomization becomes gradually stable with an increase in the GLR. It is the optimal region for the atomization, as marked by the circle. The spray effect will gradually deteriorate with an increase in the GLR.

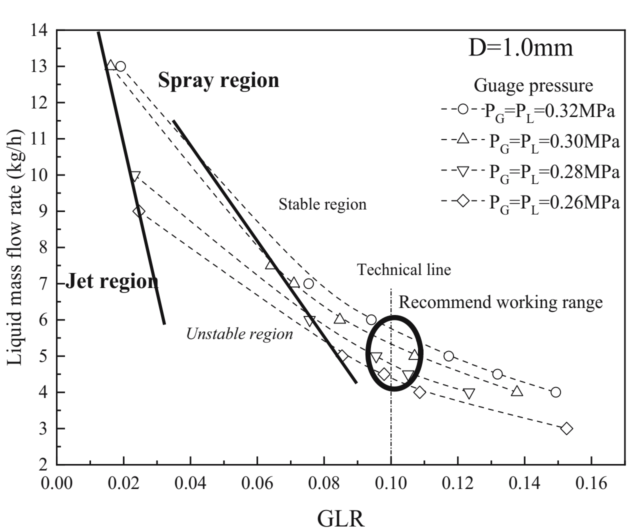

Figure 3: Characteristic of the atomization in the effervescent atomizer.

The effect of the pressure on the liquid mass flow rate is shown in Figure 3 by keeping the GLR constant. The liquid mass flow rate increases with an increase in the gas and liquid pressures. In the terms of physics, the expansion work will increase by increasing the pressure. The velocities of the atomization increases, and the liquid mass flow rate increases. The energy consumption also increases.

3.2 Effect of atomizers configuration on droplets velocity

The effect of swirl atomizer on the atomization characteristics is shown in Figure 4. The gas and liquid pressure was $p_\alpha = 0.3$ MPa ($\alpha = 1, 2$ represents liquid and gas phase, respectively). The GLR was 0.1. The distance from the discharge orifice (L) was 20–180 mm.

The radial velocity distribution of the droplets is described in Figure 4(a). The velocity of the discharge orifice center is the largest and the velocity becomes gradually small along the radial direction. The velocity radial distribution is approximately symmetrical. The velocities of the droplets will decay gradually with an increase in the distance from the discharge orifice. The SMD radial distribution of the droplets is shown in Figure 4(b). The SMD radial distribution is symmetrical. The SMD of the droplets in the discharge orifice center is the smallest and the SMD of the droplets increases gradually along the radial direction. The SMD of the droplets becomes gradually small with an increase in the distance from the discharge orifice.

3.3 Effect of GLR on droplets velocity

The velocity distribution of the droplets in the different GLR is shown in Figure 5. The GLR was changed from

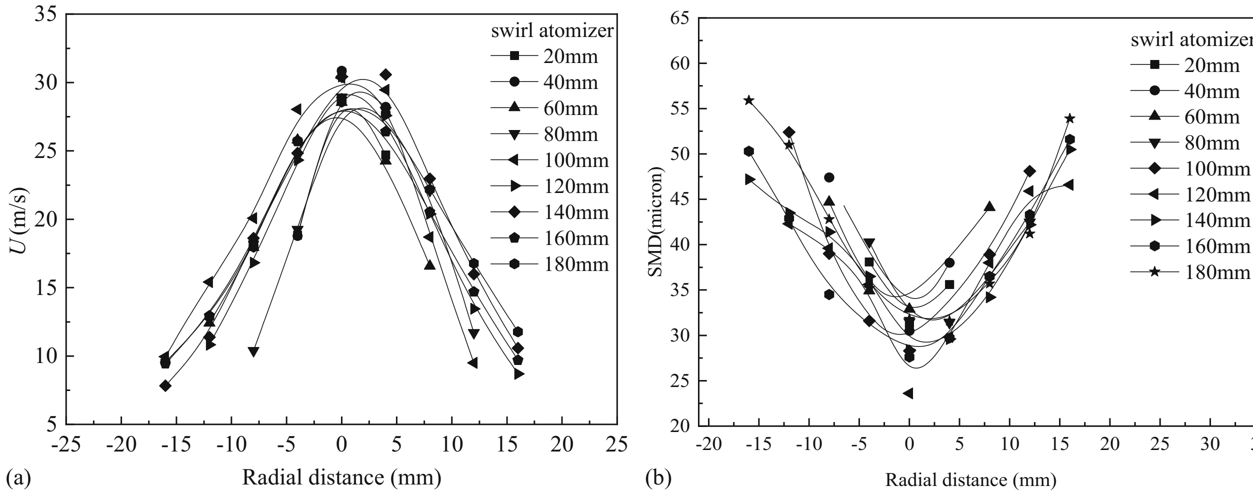

Figure 4: Characteristic of atomization. (a) Radial velocity of droplets, (b) SMD of droplets.

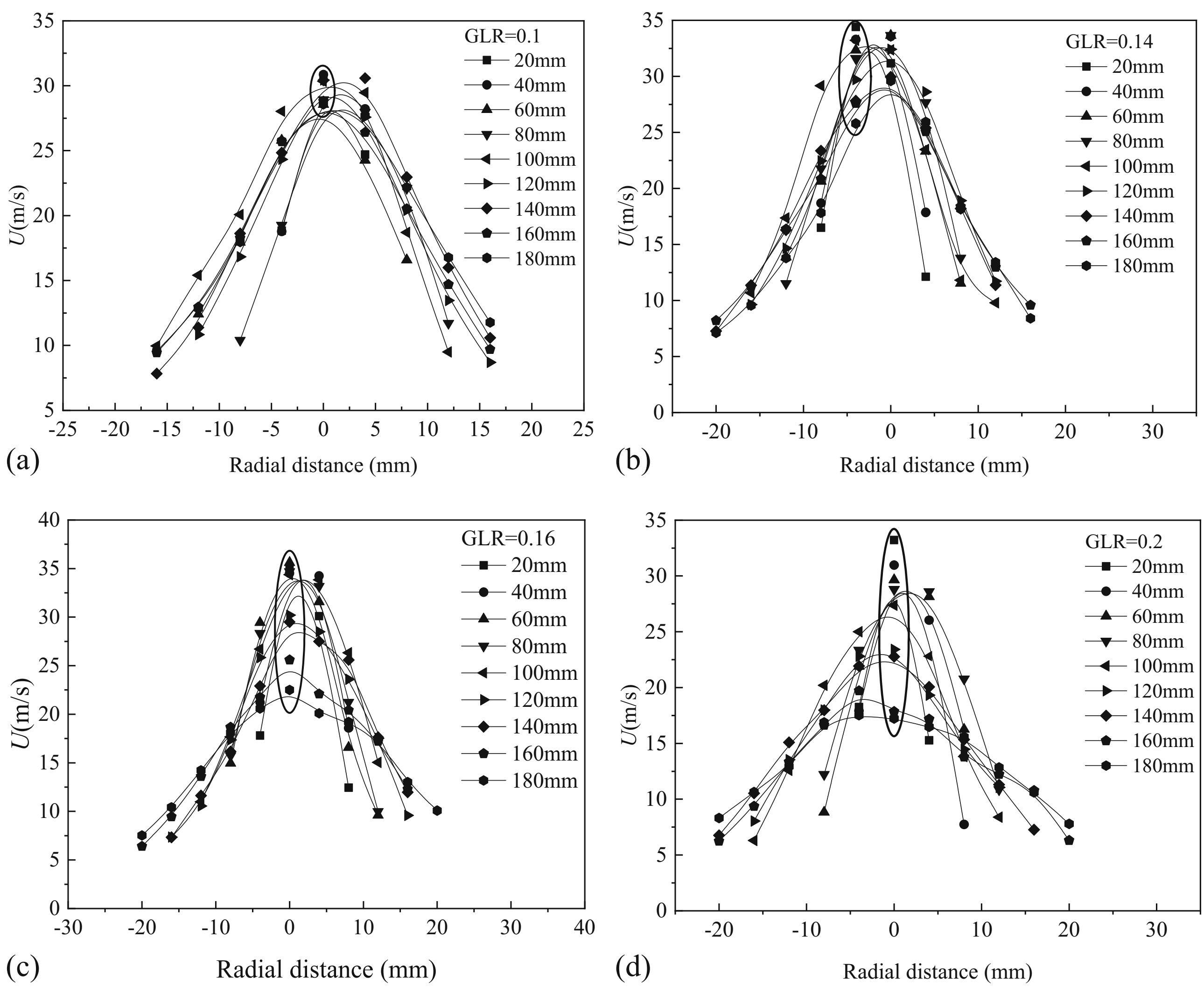

Figure 5: Effect of GLR on droplets velocity. (a) GLR = 0.1 (b) GLR = 0.14, (c) GLR = 0.16, (d) GLR = 0.2.

0.14 to 0.3 by keeping other parameters constant. The variation range (the ellipse) of the droplet velocity is relatively small at the distance from the discharge orifice (20–180 mm) for GLR = 0.1. This is an interesting phenomenon. The physical mechanisms are revealed as follows: many small bubbles are formed in the spray process. The bubbles are compressed in the atomizer interior. When the bubbles flow out of the atomizer, the bubbles would suddenly expand. At the bubble expansion process, the bubbles would deform and burst into droplets under the aerodynamic force. Some energy converts into the droplets' kinetic energy. The variation range of the droplet velocity becomes big gradually with an increase in the GLR.

3.4 Effect of GLR on droplets SMD

The SMD distribution of the droplets in the different GLR from 0.08 to 0.14 by keeping other parameters constant is described in Figure 6. The SMD decreases with an increase in the GLR from 0.08 to 0.12. The reason is that the shearing action in the gas and liquid boundary layer is further enhanced with an increase in the GLR. The liquid droplets become small in the atomization process. The atomization will become unstable with an increase in the GLR, and the size of the droplets will increase. With an increase in the GLR, the input energy also increases in the atomization process. In the following, the energy conversion will be analyzed at the stable atomization conditions.

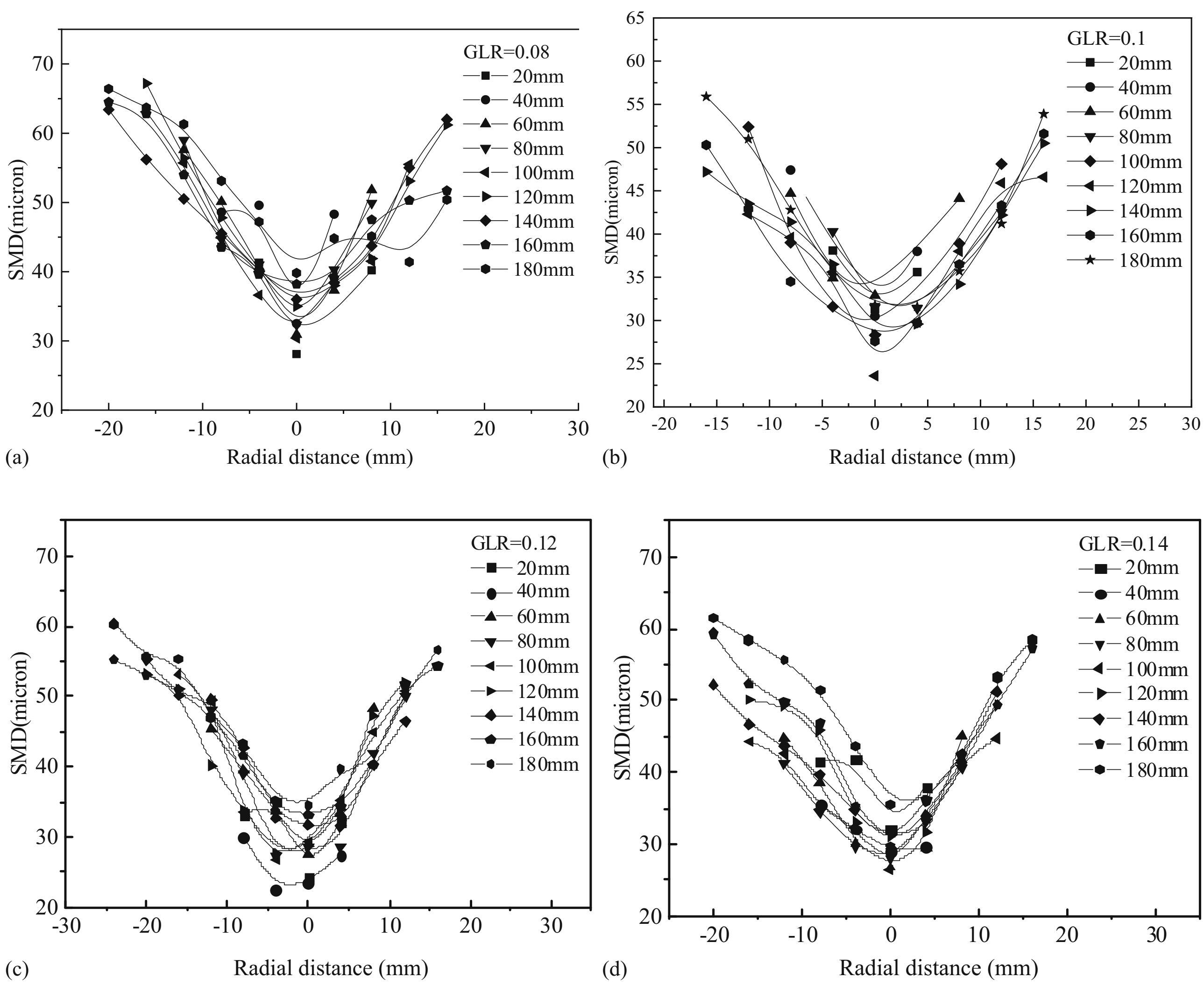

Figure 6: Effect of GLR on droplets SMD, (a) GLR = 0.08, (b) GLR = 0.1, (c) GLR = 0.12, (d) GLR = 0.14.

3.5 Energy conversion

For the effervescent atomization process, the liquid and gas mix to form bubbles inside the atomizer and are forced to spray from the atomizer outlet under the action of air pressure. The bubbles will burst near the atomizer outlet. The total input energy is balanced to the summation of the liquid surface tension energy and viscosity dissipation energy, air expansion work, spray kinetic energy and flow resistance loss, and so on, as shown in Figure 7.

The liquid flux was $M_L = 6$ kg/h. The GLR was 0.1. The gas and liquid pressure was $p_L = p_G = 0.4$ MPa. and the mixing chamber pressure was $p_c = 0.3$ MPa. The rated motor power and the rated pressure of the air compressor were 37 kW and 0.8 MPa, respectively. The rated volume flow of the air was 6.3 m^3/min. The electric efficiency and the service factor amps were defined 94.7% and 1.15, respectively. The gas compression work per unit mass was 273.16 kJ/kg. The liquid atomization rated power was 7.59 W/kg for this atomizer.

3.5.1 Total input energy

The theoretical energy for the liquid atomization can be obtained as follows:

$$w = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \text{ (kJ/kg)} \tag{1}$$

where w is the theoretical energy for the liquid atomization, n is the polytropic index in the compressing process, and P_1 and V_1 denote the pressure and volume for the atmosphere gas, respectively. The gas pressure P_2 can be generated by the compressor. The power of the input energy was calculated as 4.76 W/kg for water.

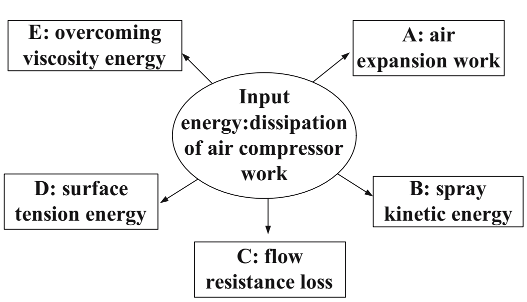

Figure 7: Energy consumption of atomizer $M_L = 6$ kg/h, GLR = 0.1, $P_L = P_G = 0.4$ MPa, $P_c = 0.3$ MPa.

3.5.2 Gas expansion work

When compressed gas is ejected into the atmospheric environment from the mixing chamber, the gas volume expansion was inevitable. The expansion work can be calculated by

$$w_1 = \frac{1}{n-1} P_1 V_1 \left[1 - \left(\frac{P_1}{P_c} \right)^{\frac{n-1}{n}} \right] \text{ (kJ/kg)} \tag{2}$$

where w_1 is the gas expansion work and P_c is the mixing chamber pressure. The power of the gas expansion work was calculated as 2.244 W/kg. The ratio of the gas expansion work to the total energy was about 47.14%.

3.5.3 Spray kinetic energy

The spray kinetic energy consisted of two parts: gas kinetic energy and liquid kinetic energy.

$$w_2 = \sum_{\alpha=1}^{2} \frac{1}{2} m_\alpha v_\alpha^2 \tag{3}$$

where w_2 is the spray's total kinetic energy, $\alpha = 1, 2$ represents liquid and gas phase, respectively, m denotes the mass of gas and liquid, and v is the velocity of gas and liquid. The power of the spray kinetic energy was obtained as 0.187 W/kg. The ratio of the spray kinetic energy to the total energy was about 3.93%.

3.5.4 Resistance losses

The atomizer system constituted of three parts, as shown in Figure 8. During the atomization process, the energy losses were mainly caused by the local resistance, especially the inlet region (abrupt contraction) and the outlet region (sudden expansion) of the discharge orifice.

$$w_3 = \zeta \frac{v^2}{2g} \tag{5}$$

where w_3 is the local resistance loss, $\zeta_1 = \zeta_3 = 0.5$ $\zeta_2 = 1$ denotes the local resistance coefficient, and v is the liquid velocity. Assuming the two-phase flow in discharge orifice was homogeneous and its velocity was nearly equal to that of spray. The power of the local resistance loss was about 0.3 W/kg.

Considering the energy losses caused by on-way resistance were the same as the local resistance loss, the power of the estimated total energy loss was about 0.6 W/kg. The ratio of the resistance losses energy to the total energy was about 12.6%.

3.5.5 Surface tension energy

$$w_4 = \sigma \frac{4\pi R^2}{N} \tag{6}$$

where w_4 is the liquid surface tension energy, σ is the liquid surface tension coefficient, R denotes the radius of the droplet, and N is the number of the droplets. The power of the surface tension energy was calculated as 0.006 W/kg. The ratio of the surface tension energy to the total energy was about 0.13%.

3.5.6 Viscosity dissipation energy

The viscosity dissipation energy was the difference between total energy and other energy. The viscosity energy can be obtained as follows:

$$w_5 = w - \sum_{m=1}^{4} w_m \tag{7}$$

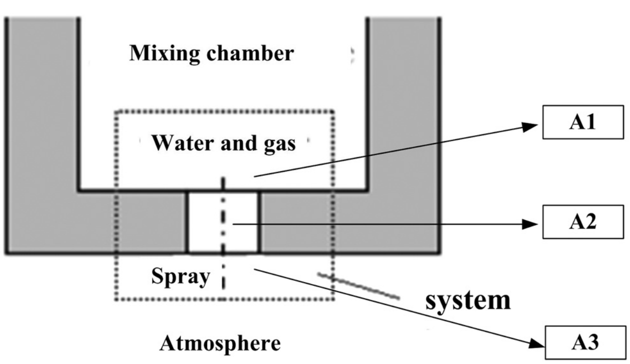

Figure 8: System diagram of atomizer.

The power of the viscosity dissipation energy was about 0.968–1.05 W/kg. The ratio of the viscous dissipation energy to the total energy was about 20.34–22.06%.

The energy equilibrium analysis results are listed in Table 1. For this effervescent atomizer, the total energy consumption was 4.76 W/kg. The energy dissipation terms were mainly compressed gas expansion (47.14%), viscosity dissipation of liquid (34.48–37.92%), and resistance losses (12.6%). The rate of gas expansion work to the total energy is most. The results are the same as the results of Jedelsky and Jicha [26]. However, the overcoming viscosity dissipation should be about 37% of the total energy. In other words, viscosity has a very important influence on the atomization process and atomization energy consumption. Hence, the viscosity dissipation is not ignored in the atomization process. The expansion cooling and heat release in the atomization process is also very important. The atomization is the process of the liquid changing into the droplets through energy conversion. In this process, expansion cooling and heat release phenomena will inevitably occur. The resistance losses in the atomizer are also an important part of the atomization process. However, the rates of the spray kinetic energy and the surface tension energy to the total energy are relatively small. Based on the above investigation and analysis, it can be concluded that further lessening the expansion work would transfer more energy to overcome liquid viscosity. In other words, the optimization design of the mixing process will be helpful to improve atomization quality.

4 Conclusions

The spray flow characteristics were experimentally diagnosed by the PDA in this article. The two atomizers were introduced and compared. The energy dissipation was analyzed by the experiments and theories. Some results can be obtained:

Table 1: Energy equilibrium analysis results

	Amount (W/kg)	Ratio (%)	Remarks
Total energy consumption	4.760	100.00	Experiments and theories
Rate of gas expansion work	2.244	47.14	Experiments and theories
Rate of viscosity dissipation	1.641–1.805	34.48–37.92	Estimated
Rate of resistance losses	0.6	12.6	Some of the assumptions
Rate of spray kinetic energy	0.187	3.93	Experiments and theories
Rate of surface tension energy	0.006	0.13	Experiments and theories

(1) When the GLR was small, the atomization is unstable work. The atomization effect becomes well gradually with an increase in the GLR. The optimal region of the atomization can be obtained.
(2) The SMD decreases with an increase in the GLR from 0.08 to 0.12. When GLR = 0.14, the atomization is unstable.
(3) The energy dissipation terms are mainly compressed gas expansion, viscosity dissipation of liquid, and resistance losses. However, the rate of the spray kinetic energy and the surface tension energy to the total energy is relatively small.

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References

[1] Jedelsky J, Jicha M, Slama J, Otahal J. Development of an effervescent atomizer for industrial burners. Energy Fuels, 2009;23:6121–30.
[2] Kermes V, Belohradsky P. Experimental study on combustion of liquid renewable fuels. In: 13th international conference on process integration, modelling and optimisation for energy saving and pollution reduction; 2010. Vol. 21, p. 457–62.
[3] Daviault S, Ramadan O, Matida E, Hughes P, Hughes R. Atomization performance of petroleum coke and coal water slurries from a twin fluid atomizer. Fuel. 2012;98:183–93.
[4] Liu G, Liu F, Yang, J, Mu Y, Hu C, Xu G. Experimental investigations of spray generated by a pressure swirl atomizer. J Energy Inst. 2018;2018:1–12.
[5] Ochowiak M, Matuszak M, Włodarczak S, Krupińska A, Markowska M, Gościniak A, et al. The concept design and study of twin-fluid effervescent atomizer with air stone aerator. Chem Eng Process Process Intensificat. 2018;124:24–8.
[6] Mahesh V, Paul E. Spatial droplet velocity and size profiles in effervescent atomizer-produced sprays. Fuel. 1999;78:729–41.
[7] Guido R. Practical and useful tips on discrete wavelet transforms. IEEE Signal Process Mag. 2015;32:162–6.
[8] Gomez J. Influence of bubble size on an effervescent atomization [MSc thesis]. University of Alberta; 2010
[9] Chen Z, Zheng D, Wang J, Chen L, Sundén B. Experimental investigation on heat transfer characteristics of various nanofluids in an indoor electric heater. Renewable Energy. 2020;147:1011–8.
[10] Guariglia E. Entropy and fractal antennas. Entropy. 2016;18:84.
[11] Berry M, Lewis Z. On the Weierstrass–Mandelbrot fractal function. Proc R Soc A. 1980;370:459–84.
[12] Lefebvre AH, Wang XF, Martin CA. Spray characteristics of aerated-liquid pressure atomizers. J. Propul. Power. 1988;4:293–8.
[13] Zheng D, Wang J, Chen Z, Baleta J, Sundén B. Performance analysis of a plate heat exchanger using various nanofluids. Int J Heat Mass Transfer. 2020;158:119993.
[14] Lefebvre AH, Wang XF, Martin CA. Spray characteristics of aerated-liquid pressure atomizers. J Propuls Power. 1988;4:293–8.
[15] Wade RA, Weerts JM, Sojka PE, Gore JP, Eckerle WA. Effervescent atomization at injection pressures in the MPa range. Atomizat Sprays. 1999;9:651–67.
[16] Wang J, Tian K, Zhu H, Zeng M, Sundén B. Numerical investigation of particle deposition in film-cooled blade leading edge. Numer Heat Transfer Part A Appl. 2020;77:579–98.
[17] Satapathy MR, Sovani SD, Sojka PE, Gore JP, Eckerle WA, Crofts JD. The effect of ambient density on the performance of an effervescent atomizer operating in the MPa injection pressure range. In: Proceedings of the CSS/CI 1998 technical meeting, 76–80, Lexington, KY (June 1998).
[18] Sovani S, Sojka P, Lefebvre A. Effervescent atomization. Progr Energy Combust Sci. 2001;27:483–521.
[19] Bayvel LP. Liquid atomization. New York: Routledge; 1993.
[20] Karnawat J, Kushari A. Controlled atomization using a twin-fluid swirl atomizer. Exp Fluids. 2006;41:649–63.
[21] Sovani SD, Chou E, Sojka PE, Gore JP, Eckerle WA, Crofts JD. High pressure effervescent atomization: effect of ambient pressure on spray cone angle. Fuel. 2001;80:427–35.
[22] Chen SK, Lefebvre AH. Spray cone angles of effervescent atomizers. Atomizat Spray. 1994;4:291–301.
[23] Ochowiak M, Broniarz-Press L, Rozanski J. The discharge coefficient of effervescent atomizers. Exp Therm Fluid Sci. 2010;34:1316–23.
[24] Lefebvre AH. Energy considerations in twin-fluid atomization. J Eng Gas Turbines Power Trans ASME. 1992;114:89–96.
[25] Beck JE, Lefebvre AH, Koblish TR. Airblast atomization at conditions of low air velocity. J Propuls Power. 1991;7:207–12.
[26] Jedelsky J and Jicha M. Energy conversion during effervescent atomization. Fuel. 2013;111:836–44.