CHEMICAL ENGINEERING TRANSACTIONS

VOL. 35, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis

ISBN 978-88-95608-26-6; **ISSN** 1974-9791

DOI: 10.3303/CET1335189

Experimental Investigations of Effervescent Atomization Using Non-intrusive Techniques

Jakub Broukal[a], Jiří Hájek[*a], Paul E. Sojka[b]

[a]Institute of Process and Environmental Engineering, Faculty of Mechanical Engineering, Brno University of Technology Technická 2896/2, 616 69 Brno, Czech Republic;
bMaurice J. Zucrow Laboratories, School of Mechanical Engineering, Purdue University West Lafayette, IN 47907-1003, USA
hajek@fme.vutbr.cz

Although effervescent atomizers (twin fluid atomizers with internal mixing) represent one of the most recent atomization techniques, they have already shown great usability especially in combustion applications. Due to their different drop formation mechanism they are able to produce smaller droplets than many other conventional atomizers at similar operating conditions, thus making the combustion process more efficient. However, one of the shortcomings of effervescent atomization is the complexity of the atomization mechanism, which involves a two-phase flow. This complexity presents a challenging obstacle when trying to devise computational models describing effervescent sprays. In the past few years many various models have been proposed, but their verification and validation often relies only on very limited data, such as only few representative diameters.
The purpose of this paper is to review the previous experimental studies on effervescent atomization in order to identify areas that need to be more deeply investigated. The parameters that need more detailed analysis include especially radially (or angularly) and axially dependent representative drop diameters or drop distributions and mass fluxes. It is shown that previous measurements did not collect sufficient amount of data across the whole spectrum of drop sizes and thus parts of the previously measured spectra might be unreliable. A methodology for effervescent spray measurement for verification and validation of numerical models for combustion applications is suggested. A possible need of blending drop size distribution functions from multiple measurements is also highlighted.

1. Introduction

Spray combustion is one of the main ways to gain energy in the power and process industries. A great deal of effort is therefore constantly being put into understanding of the fundamental phenomena and processes governing spray formation. These efforts are motivated by the need to achieve better performance, lower emissions and longer lifetime of furnaces and combustors in various industrial applications.
For combustion purposes, effervescent atomizers are gaining on popularity. They were first introduced by Lefebvre and his colleagues in the late 1980s (Lefebvre et al., 1988). The spray formation process in this type of atomizers does not rely solely on high liquid pressure and aerodynamic forces. Instead, a small amount of gas (typically air) is introduced in the liquid before it exits the atomizer and a two phase flow is formed (Figure 1). When the mixture exits through the nozzle, pressure suddenly drops, which causes fast expansion of gas bubbles and breakup of the liquid fuel into ligaments and subsequently droplets. As noted in (Babinsky and Sojka, 2002), this breakup mechanism allows to use lower injection pressures and larger nozzle diameters without compromising the drop-size distribution.
Recently a great effort has been put into finding reliable numerical models that would describe effervescent spray formation. Many models for various applications have been proposed, however, before they can be successfully applied to industrial applications proper verification and validation needs to be done.

Please cite this article as: Broukal J., Hajek J., Sojka P.E., 2013, Experimental investigations of effervescent atomization using non-intrusive techniques, Chemical Engineering Transactions, 35, 1135-1140 DOI:10.3303/CET1335189

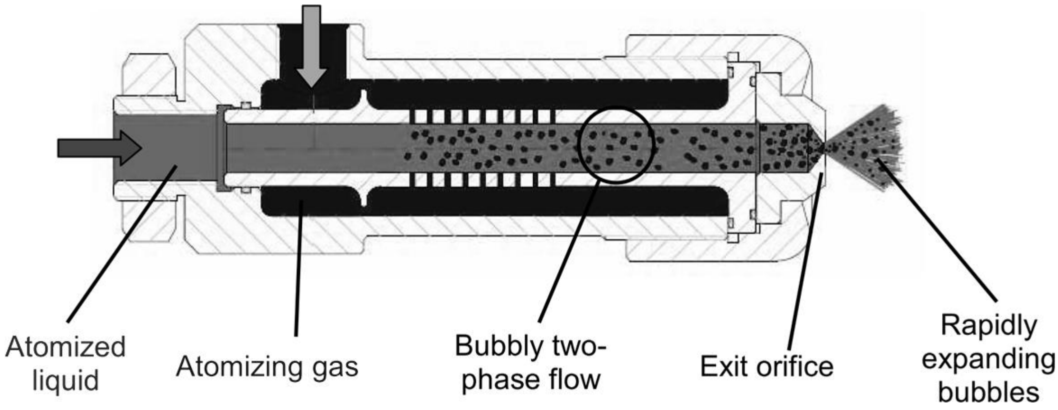

Figure 1: Schematics of the effervescent atomization process, reprinted from (Jedelský et al., 2007)

In the area of combustion, spray models are usually validated based on their ability to predict the Sauter Mean Diameter (SMD). The Sauter Mean Diameter is defined as a diameter of a representative droplet having the same volume/surface area ratio as the whole spray. As pointed out in (Broukal and Hájek, 2011a), this can be a very rough approach, since even if the global SMD of the spray in question is in good agreement with measurements, local SMD values might be different and thus cause faulty numerical predictions. Moreover, as shown long time ago by Juslin et al. (1995) and recently again by Broukal and Hájek (2011b), effervescent sprays often exhibit multimodal behaviour in drop size distributions, which further raises the question about legitimacy of using a single representative diameter (see Figure 2 and Figure 3). To remedy this, more detailed information would be needed to make really sensible validations. Namely, data about radial (or equivalently depending on spray angle) distribution of droplet size and velocity would be desirable, especially for the case of large nozzles in industrial burners.

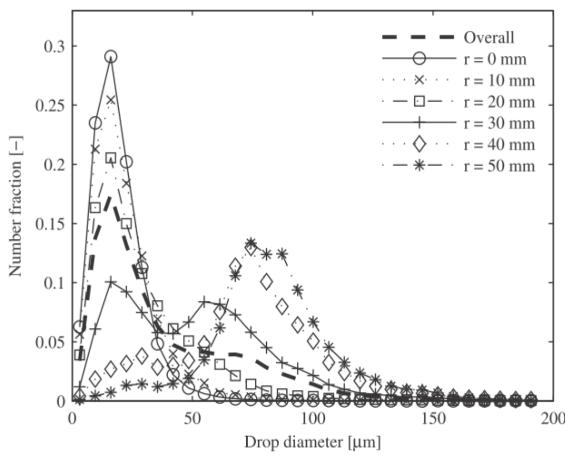

Figure 2: Example of bimodality, reprinted from (Broukal and Hájek, 2011b)

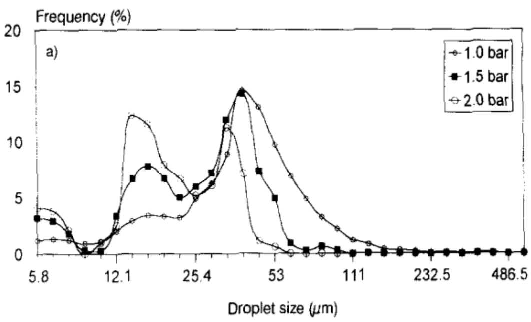

Figure 3: Example of bimodality, reprinted from (Juslin et al., 1995)

2. Current measurement approaches

Currently, spray model validation studies compare numerical results with experiments usually only in terms of global SMD or its axial evolution. Apte et al. (2003) predict axial SMD evolution in a diesel engine using a proposed hybrid particle-parcel model coupled with a LES solver, but only a single experimental SMD value is used in the comparison. A model for atomization of viscous and non-Newtonian liquids in an air-blast atomizer is described by Aliseda et al. (2008) and validated in terms of axial SMD evolution. Tembley et al. (2011) predicted drop size distribution in ultrasonic atomizers. His group developed a model able to predict initial drop size distribution as well as how does the distribution change along the spray axis. However, this model only predicts the overall drop size distribution of a spray cross-section at a specified axial distance. In (Mandato et al., 2012) both single and two-fluid atomizers are examined. A model for spray formation based on dimensional analysis is developed, which is validated using a single point measurement

In the last decade few papers can be found that address the issue of radial drop size distribution and radial SMD evolution. Park et al. (2009) employed the wave breakup model to investigate biodiesel spray in various fuel and ambient conditions in terms of axial and radial SMD evolution. Along with axial SMD evolution, also radial SMD evolution was reported. Unfortunately, only three radial SMD were disclosed. In (Pougatch et al., 2009) a spray model is presented and applied to water air-assisted atomization. Radial drop diameter evolution is predicted at various axial positions, but no comparison with experimental data has been made. Recently the situation has improved as more researchers focus in more detail on a complex spray measurement (Li et al., 2012). Lian-sheng et al. (2012) performs a detailed experimental measurement of effervescent spray combustion. The work reports various radial SMD and axial drop size distributions. Also, a swirl effervescent atomizer is employed and the influence of swirl on spray angle is demonstrated. However, the liquid mass flow rates are still in a lab-scale region with a maximum of only 10 kg/h.

These examples illustrate the pressing need for validated spray models that would include sufficient information for an informed choice of models by Computational Fluid Dynamics (CFD) analysts in the industry. Although many research papers have been published about atomization and drop breakup, so far only little attention is given to radial SMD or more detailed spatial drop-size distribution, especially in large-scale effervescent atomizers.

3. Measurement techniques

In this section the main idea is to provide the reader with an overview of the most used measurement techniques used in the area of spray measurements, especially droplet size measurements, with emphasis on the Phase/Doppler Particle Analyser (P/DPA) or sometimes also called Phase Doppler Anemometry (PDA).

3.1 Phase Doppler Anemometry

The Phase Doppler Anemometry is an extension of the Laser Doppler Anemometry used mainly to study local velocities (up to 3 components) in fluid flows. The extension lies in the ability to measure diameters of particles present in the fluid flow (bubbles in liquid, droplets in gas etc.). The PDA is a non-intrusive optical technique, on-line and in-situ. Due to the nature of the technique, optical access to the measurement area is needed, which can be sometimes limiting for on-site industrial measurements. Since the method requires particles to be spherical (or only slightly deformed), measurements must be taken at a sufficient distance from the discharge orifice. Also, the method is not suitable for very dense spray regions. The measurement device consists of a laser based optical transmitter, an optical receiver, a signal processor and software for data analysis. The laser beams emitted by the transmitter intersect creating a small sample volume. When a droplet passes through this laser intersection the scattered light forms a fringe pattern. As the drop moves, the scattered interference pattern is registered by the receiver at the Doppler difference frequency, which is proportional to the drop velocity. The droplet diameter is then inversely proportional to the spatial frequency of the fringe pattern. Due to the purely optical nature of the measurement process, no calibration is required and since the sampling volume is usually very small (1 mm^3) high spatial resolution can easily be achieved.

This technique is ideal for high precision measurements of liquid sprays and its results can be used to perform detailed validation of numerical models. Although it gives excellent qualitative representation of the spray (local drop size and velocity distributions), quantitative results, such as mass concentration, can be misleading as reported by some time ago by Babinsky and Sojka (2002) and recently again by Broukal et al. (2010). This is most probably the result of the trade-off for high spatial resolution and possibly also due to rejection of non-spherical droplets.

3.2 Other techniques

An alternative to PDA is provided by the so called whole-flow-field techniques, like Particle/Droplet Imaging Analysis (PDIA) or Particle Image Velocimetry (PIV). These non-intrusive techniques were originally devised to measure velocity fields of seeded flows. The basic principle of these methods is to take two consecutive images of an illuminated cross-section of the flow and by comparing the displacement of the particles compute the velocity vector field. Moreover, information about drop diameters can be gathered as well by employing advanced image processing algorithms (Avulapati and Ravikrishna, 2012).

To remedy the potential inaccuracy of mass concentration measurements in the PDA measurements, Planar Laser-Induced Fluorescence (PLIF) can be employed as shown by Jedelsky and Jicha (2012).

During the measurement, a spray cross-section is shortly illuminated by a laser sheet and after some time (in the order of nano- or microseconds) the droplets de-excite and emit a portion of the light which is captured by a camera. The emitted light intensity is proportional to the liquid concentration.

4. Methodology of spray characterization

This section will aim at providing guidelines for gathering ideal experimental data of effervescent sprays to be used for validation of numerical spray models. From the previous section it is evident, that in order to get high resolution drop size and velocity measurement together with accurate mass concentration information, two measurement techniques need to be employed. However, in this part emphasis will be put on the PDA measurement technique.

For the purpose of model development and validation, the primary breakup region of the spray is the most important. Unfortunately, due to the limitations of the PDA technique we cannot measure the spray at its origin, since the droplets are far from being spherical and also the liquid density might be too high. The goal then is to get as close to the spray nozzle as possible. Li et al. (2012) demonstrated that PDA measurements can be taken at distance from the spray origin $x^* = x/d_0 = 3.3$ (where x is axial distance and d_0 is the discharge orifice diameter), which can still be regarded as area dominated by primary atomization. Data collected here can be a good starting point for the model validation and can even be used as boundary conditions for CFD simulation if needed. After the closest possible location to the spray nozzle has been identified, the set of measurement points should be then expanded in the radial direction to the spray edge using at least two new locations. If the drop size distributions or SMD measurements vary substantially between these points, additional measurement locations should be introduced. To understand the axial evolution of the spray, this process should be repeated at least once more further downstream. The number of radial measurement points should be increased since the spray cone naturally widens. The radial measurements can be taken in multiple directions to check the symmetric behaviour of the spray.

When performing a PDA measurement the user has to choose a receiver mask based on the expected range of drop diameters. If the range of generated droplets does not fall in the range specified by the mask, a part of the drop size distribution will be trimmed. It is therefore advisable to perform measurements with multiple masks and eventually merge resulting distributions. In such case the distributions must be weighted properly prior to merging and also, attention must be paid to whether the mask ranges overlap.

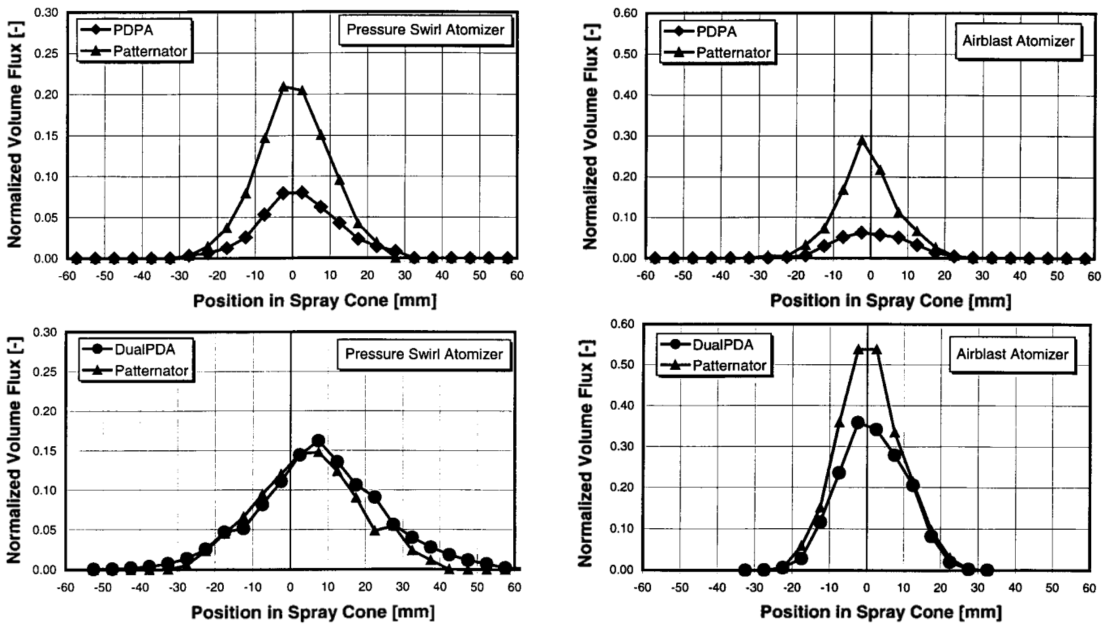

Figure 4: Comparison of volume flux measurements for two types of atomizer using different measurement techniques, reprinted from (Dullenkopf et al., 1998)

One of the parameters influencing the quality of measured data is the number of sampled droplets. It is reasonable to expect, that the actual drop size distributions are smooth, including the peripheries or so called tails, where the droplet fraction is small. To obtain such distribution it is important to sample a sufficient number of droplets. Various sampling numbers are adopted, form 2,000 (Li et al., 2012), 10,000 (Panchagnula and Sojka, 1999), 20,000 (Jedelský et al., 2004) up to 50,000 and 100,000 (Liu et al., 2010). There is no universal rule to determine this number, but it can be derived during the measurement itself by judging on the convergence of the drop size distribution. In some cases the smoothness of the drop size distribution might be also compromised by a wrong choice of mask, or by high noise. The latter case can be remedied by shielding the measurement area from any other light sources and/or by increasing the PDA lasers power.

As mentioned above, accurate measurement of liquid mass concentration and mass flux are a vital part for successful numerical validation, especially in the area of spray combustion. The PDA technique is known to have issues when measuring mass concentration as noted in 3.1. However, in (Dullenkopf et al., 1998) it is shown, that the Dual PDA technique (an extension of PDA combining conventional PDA and planar PDA) gives much better results. Dullenkopf compares flux measurements of PDA, Dual PDA and patternator, showing a noticeable improvement for Dual PDA over the conventional PDA (see Figure 4). He takes into account a pressure swirl and airblast atomizer and there is no reason not to assume a similar improvement would be observed in the case of effervescent atomizers. Naturally, this needs to be confirmed by dedicated experimental measurement.

5. Conclusions

The present work provides an overview of spray measurements with emphasis on effervescent spray formation and stresses the need of experimental data for verification and validation of numerical spray models for combustion purposes. It is shown that a great deal of available experimental results are insufficient for validation of numerical models, since only a coarse and global representation of the spray is given. Furthermore it is highlighted, that higher spatial resolution of measurements is needed, although recently detailed studies started to appear, for example in (Li et al., 2012) and also (Lian-sheng et al., 2012).

Furthermore, a methodology for effervescent spray measurement using PDA technique is suggested that produces experimental results suitable for numerical model validations. Ideally, at least two sets of radial measurements points at various axial locations should be performed focusing on drop size and velocity distributions and also on mass flux distribution. Attention must be paid to the mask choice in order to prevent trimming of the drop distributions. The issue of unreliable mass flux measurements using PDA is addressed, but it is shown, that the Dual PDA extension of the original technique is able to at least partially overcome this problem. However, a similar study to that of (Dullenkopf et al., 1998) needs to be performed for the case of effervescent atomization.

6. Acknowledgements

The present work has been supported by European Regional Development Fund in the framework of the research project NETME Centre under the Operational Programme Research and Development for Innovation, reg. number CZ. 1.05/2.1.00/01.0002 and by the Fulbright Scholarship Grant.

References

Aliseda, A., Hopfinger, E. J., Lasheras, J. C., Kremer, D. M., Berchielli, A., Connolly, E. K., 2008, Atomization of viscous and non-newtonian liquids by a coaxial, high-speed gas jet. Experiments and droplet size modeling, International Journal of Multiphase Flow, 34(2), 161–175.

Apte, S. V., Gorokhovski, M., Moin, P., 2003, LES of atomizing spray with stochastic modeling of secondary breakup, International Journal of Multiphase Flow, 29(9), 1503–1522.

Avulapati, M. M., Ravikrishna, R. V., 2012, An Experimental Study on Effervescent Atomization of Bio-oil Fuels, Atomization and Sprays, 22(8), 663–685.

Babinsky, E., Sojka, P. E., 2002, Modeling drop size distributions, Progress in Energy and Combustion Science, 28(4), 303–329.

Broukal, J., Hájek, J., 2011a, Effervescent Spray Modelling: Investigation of Drop Momentum Models and Validation by Measured Data, Chemical Engineering Transactions, 25(1), 797–802.

Broukal, J., Hájek, J., 2011b, Validation of an effervescent spray model with secondary atomization and its application to modeling of a large-scale furnace, Applied Thermal Engineering, 31(13), 2153–2164.

Broukal, J., Hájek, J., Jedelský, J., 2010, Effervescent atomization of extra-light fuel-oil: Experiment and statistical evaluation of spray characteristics, in Proceedings of 23rd European Conference on Liquid Atomization and Spray Systems, 23, 1–10, Brno, Czech Republic.

Dullenkopf, K., Willmann, M., Wittig, S., Schöne, F., Stieglmeier, M., Tropea, C., Mundo, C., 1998, Comparative Mass Flux Measurements in Sprays using a Patternator and the Phase-Doppler Technique, Particle and Particle Systems Characterization, 15(2), 81–89.

Jedelsky, J., Jicha, M., 2012, Spatially and Temporally Resolved Distributions of Liquid in an Effervescent Spray, Atomization and Sprays, 22(7), 603–626.

Jedelský, J., Jícha, M., Otáhal, J., Katolický, J., Landsmann, M., 2007, Velocity field in spray of twin-fluid atomizers, in 21st Sympozium on Anemometry, Proceedings, 67–74, Prague, Czech Republic.

Jedelský, J., Jícha, M., Sláma, J., 2004, Characteristics And Behaviour Of Multi-Hole Effervescent Atomizers, in 19th International Conference on Liquid Atomization and Spray Systems - ILASS Europe, 521–526, Nottingham, UK.

Juslin, L., Antikainen, O., Merkku, P., Yliruusi, J., 1995, Droplet size measurement: I. Effect of three independent variables on droplet size distribution and spray angle from a pneumatic nozzle, International Journal of Pharmaceutics, 123(2), 247–256.

Lefebvre, A. H., Wang, X. F., Martin, C. A., 1988, Spray Characteristics of Aerated-Liquid Pressure Atomizers, Journal of Propulsion and Power, 4(4), 293–298.

Li, Z., Wu, Y., Cai, C., Zhang, H., Gong, Y., Takeno, K., Hashiguchi, K., Lu, J., 2012, Mixing and atomization characteristics in an internal-mixing twin-fluid atomizer, Fuel, 97, 306–314.

Lian-sheng, L., Hua, Y., Xiang, G., Runze, D., Yan, Y., 2012, Experimental Investigations on the Spray Combustion Produced by Effervescent Atomizers, in 2012 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM), pp. 305 –311.

Liu, M., Duan, Y., Zhang, T., 2010, Evaluation of effervescent atomizer internal design on the spray unsteadiness using a phase/Doppler particle analyzer, Experimental Thermal and Fluid Science, 34(6), 657–665.

Mandato, S., Rondet, E., Delaplace, G., Barkouti, A., Galet, L., Accart, P., Ruiz, T., Cuq, B., 2012, Liquids' atomization with two different nozzles: Modeling of the effects of some processing and formulation conditions by dimensional analysis, Powder Technology, 224, 323–330.

Panchagnula, M. V., Sojka, P. E., 1999, Spatial droplet velocity and size profiles in effervescent atomizer-produced sprays, Fuel, 78(6), 729–741.

Park, S. H., Kim, H. J., Suh, H. K., Lee, C. S., 2009, Experimental and numerical analysis of spray-atomization characteristics of biodiesel fuel in various fuel and ambient temperatures conditions, International Journal of Heat and Fluid Flow, 30(5), 960–970.

Pougatch, K., Salcudean, M., Chan, E., Knapper, B., 2009, A two-fluid model of gas-assisted atomization including flow through the nozzle, phase inversion, and spray dispersion, International Journal of Multiphase Flow, 35(7), 661–675.

Tembely, M., Lecot, C., Soucemarianadin, A., 2011, Prediction and evolution of drop-size distribution for a new ultrasonic atomizer, Applied Thermal Engineering, 31(5), 656–667.