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Interpreting Liquid Atomization Efficiency

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Abstract: Liquid atomization involves several mechanisms transforming a bulk of liquid into small droplets. The atomization efficiency usefulness is questionable considering its low values (0.01-1%). This work presents a general definition for atomization efficiency and explains why the Sauter mean diameter is the appropriate characteristic drop size (and no other mean diameter value). Finally, future directions are suggested for developing injector design tools from atomization efficiency.

Introduction

In liquid atomization, the production of small droplets from a liquid bulk is a physical event dominated by surface energy transfer. The liquid atomization efficiency relates the interfacial energy change between the initial liquid bulk and the spray droplets, with the input energy available depending on the atomization strategy. However, Jedelsky et al. [1] showed that surface energy represents a small portion of the input energy at the nozzle inlet considering all friction losses, the kinetic energy transported by the liquid, air, and their interaction, and the energy associated with acoustic and thermal effects during atomization. Therefore, the scales for the atomization efficiency range between relatively low values of 0.01-1%.

In their reference textbook on "Atomization and Sprays," Lefebvre et al. [2] associated the quality or fineness of liquid atomization to the characterization of atomizer performance but do not analyze the atomization efficiency or interpret it. Most works reported on spray characterization consider the atomization efficiency as one of the parameters inside empirical correlations developed to predict the spray droplets' mean diameter. And the most used mean quantities are the Sauter Mean Diameter (SMD or d_{32}) and the Arithmetic Mean Diameter (AMD or d_{10}). But, while the SMD is "the most widely" [2] used parameter for these correlations, Lefebvre et al. [2] do not explain the reason. And while several researchers argue the reason is "obvious," such affirmation still needs grounding in a physical explanation. This mini-review explores this reason.

Furthermore, Lefebvre [3] is among the first works containing the fundamental insights into a systematic characterization of the atomization efficiency, introducing the physical analysis of the surface atomizing energy between a flat-sheet or plain-jet liquid bulk and the spray droplets, but lacks a general treatment to any hydrodynamic structure of the liquid bulk. Therefore, this work attempts to develop a general definition of atomization efficiency followed by its interpretation. Additionally, one assesses this definition as a performance index, comparing with previous work for an air-assisted multiple impinging jets spray. And, finally, one presents future directions for atomization efficiency as a design tool to explore new liquid atomization strategies.

What is Liquid Atomization's General Definition?

Liquid atomization concerns the change in surface energy between the total surface energy in the initial hydrodynamic structure of a bulk liquid ($E_L = \sigma_L A_L$), and the surface energy of the spray droplets after atomization ($E_d = \sigma_L A_d$), with σ_L $[N/m]$ as the liquid (L) surface tension, A_L as the bulk liquid surface area, and A_d as the total surface area of the spray droplets.

The total surface energy of the bulk liquid before atomization depends on its geometry. Namely, it could be a cylinder, a sheet, or any other liquid structure. The interfacial change of surface energy in the atomization of a bulk liquid is the difference between the final and initial stages: $E_a = E_d - E_L$. In general, considering the energy initially available for liquid atomization as E_i, the atomization efficiency results in:

$$\eta_a = \frac{E_a}{E_i} \quad (1)$$

Assuming the mass of this initial liquid structure m_L is fully converted into droplets, $m_d = m_L$, one can divide each term in Eq. (1) by the atomized mass and obtain the atomization efficiency as a function of specific energy. In the numerator, the atomization specific energy depends on the difference between the final and initial specific surface area of the spray droplets and bulk liquid, respectively.

$$e_a = \frac{E_a}{m_L} \underbrace{=}_{m_d = m_L} \sigma_L\left(\frac{A_d}{m_d} - \frac{A_L}{m_L}\right) \quad (2)$$

In the initial state, one could generally express the liquid bulk mass as $m_L = \rho_L A_L L_c$, with L_c as the characteristic length of the initial bulk liquid. Thus,

$$\frac{A_L}{m_L} = \frac{1}{\rho_L L_c} \quad (3)$$

For the N spray droplets, the specific surface area is

$$\frac{A_d}{m_d} = \frac{\pi \sum_{i=1}^{N} d_i^2}{\rho_L \frac{\pi}{6} \sum_{i=1}^{N} d_i^3} = \frac{6}{\rho_L}\left(\frac{\sum_{i=1}^{N} d_i^3}{\sum_{i=1}^{N} d_i^2}\right)^{-1} = \frac{6}{\rho_L d_{32}} \quad (4)$$

with $d_{32} = \frac{\sum_{i=1}^{N} d_i^3}{\sum_{i=1}^{N} d_i^2}$ as the Sauter mean diameter (SMD), or surface-weighted mean diameter, according to Sowa's [4] interpretation. This result provides some insight into the physical meaning worthy of a comment made later.

Considering the specific initial energy available for atomizing the liquid bulk as $e_i = E_i/m_L$, and using Eqs. (3) and (4) in (1), the general expression for the liquid atomization efficiency becomes

$$\eta_a = \frac{e_a}{e_i} = \frac{\sigma_L}{\rho_L}\left(\frac{m_L}{E_i}\right)\left[\frac{6}{d_{32}} - \frac{1}{L_c}\right] \quad (5)$$

and its interpretation regarding an efficient liquid atomization implies:

a. a large initial bulk liquid mass (m_L),

b. with a large characteristic length (L_c),

c. uses a small amount of initial available energy (E_i),

d. to produce droplets of the tiniest size (d_{32}).

Also, if we consider the mass flow rate of liquid injected, $m_L/E_i = \dot{m}_L/\dot{E}_i$, with $\dot{E}_i$ as the energy rate initially available for atomization. The characteristic length (L_c) and the energy initially available for atomization depend on the atomizer type and atomization strategy.

The formulation in Eq. (5) is universal, and one can interpret it as the work done in the interfacial energy exchange from the initial bulk liquid structure to the spray droplets, expressed as $e_a = \rho_L^{-1}(1.5p_{c,d} - p_{c,L}) \sim \Delta p_c/\rho_L$, with $p_{c,L} = \sigma_L/L_c$ as the capillary pressure of the initial bulk liquid structure, and $p_{c,d} = 4\sigma_L/d_{32}$ as the capillary pressure of the spray droplets. Therefore, another interpretation for the general expression derived for the atomization efficiency is to express it in terms of the ratio between a capillary pressure differential and an input volumetric energy ($E_i''' = \rho_L E_i/m_L\ [J/m^3] \equiv [N/m^2]$) as

$$\eta_a = \frac{1.5p_{c,d} - p_{c,L}}{E_i'''} \quad (6)$$

If the input volumetric energy used to atomize is different from the hydrodynamic kind, one can replace this term for the appropriate one. For example, if the input energy for atomizing the bulk liquid is electrical as in charge hydrocarbon sprays, the volumetric input energy used is $E_i''' = \rho_v \varphi$, with ρ_v $[C/m^3]$ as the spray specific charge and φ $[V]$ the voltage [5]. Or in the case of effervescent sprays, the input volumetric energy corresponds to the input work exerted by the pressurized dissolved gas into the liquid bulk before the atomizer injector nozzle exit and is expressed as $E_i''' = p_L + ALR \cdot \rho_* p_\infty (1 + p_A^\infty) \cdot ln(1 + p_A^\infty)$, with p_L as the liquid pressure, p_∞ the atmospheric pressure, and p_A^∞ as the pressure of the dissolved gas normalized by p_∞ [6]. However, when we express the atomization efficiency as a function of an input volumetric energy, we could also interpret it as an input dynamic pressure that can generate differences in the results obtained for the atomization efficiency as observed by Xia et al. [7] for air-assisted multiple-impinging jets spray.

Xia et al. [7] analyzed two atomization efficiencies applied to sprays produced by the impact of multiple impinging jets, assisted by a central air jet:

a. The atomization efficiency defined by Lefebvre [3] for airblast atomizers considering the input dynamic pressure of the air, $E_i = \frac{1}{2} m_A U_A^2$, as the sole term, resulting in $E_i''' = \frac{\rho_L}{2} ALR \cdot U_A^2$ with ALR as the Air-to-Liquid Ratio based on the mass or mass flow rate;

b. And what Pizziol et al. [6] defined by atomization efficiency for air-assisted multiple impinging jets, although, as explained below, it is a misleading term, and a closer analysis of their approach show they defined a new functional relation that evaluates the *atomization performance* in need of further clarification.

Pizziol et al. [8] related the capillary forces involved in the conversion of a liquid bulk into droplets (through a capillary pressure differential) with the input impact force of each jet and the air stream given by the total dynamic pressure as $p_i = N_j \cdot p_j + p_A$, with $p_j = \frac{1}{2}\rho_L U_j^2$ and $p_A = \frac{1}{2}\rho_A U_A^2$. Although these authors considered the capillary pressure of the liquid jets before atomization, it is negligible compared to the dynamic pressure. This ratio generated a new functional relation helpful in evaluating the atomizer performance, $\zeta_a = \frac{1.5p_{c,d} - p_{c,L}}{p_i}$, with an advantage explained later.

Considering the clarification above, if we define the volumetric input energy for air-assisted multiple-impinging jets as the summation of the kinetic energy terms of all liquid jets and the air as $E_i = N_j E_{k,j} + E_{k,A}$, the result would be similar to Lefebvre [3] and produce similar atomization efficiency values.

$$E_i''' = \frac{\rho_L}{2}\left(U_j^2 + ALR \cdot U_A^2\right) \quad (7)$$

Figure 1 compares the atomization efficiency with the new performance index. The purpose of using an air jet in a multiple-impinging jet atomizer is to assist the atomization process and produce smaller droplets. From the energetic point of view, an air-assisted atomizer generates smaller droplets (Figure 1 – right) but at an energetic cost shown through the decrease of η_a. However, considering the atomization performance ζ_a, as a design tool, it indicates a higher ALR correlates with smaller d_{32} (Figure 1 – right), which is coherent with a design performing better as visualized and expected.

However, although the atomization performance can be a valuable injector design tool, the atomization efficiency allows a better understanding of the Sauter Mean Diameter's physical meaning.

What Insight Liquid Atomization Provides about the Physical Meaning of the Sauter Mean Diameter?

Any mean drop size expresses the equivalence between the polydispersed sizes of droplets in a spray and a spray made of single-size (or monodispersed) droplets. Kowalczuk et al. [9] give a step forward and associate the physical meaning of the SMD (d_{32}) as the representative size of a monodispersed spray with the same surface energy as the polydispersed spray. However, this physical meaning is not directly related to the liquid atomization physical process.

In the earlier work of Evers [10], similarly to Lefebvre [3], the author analyzes atomization from energy conservation. And while defining the specific surface area of the spray droplets, a_d [m^2/kg], Evers [10] arrives at an expression involving a characteristic diameter related to the liquid volume and states the «*Sauter mean diameter (SMD) is by definition the diameter of a droplet having the same ratio of volume to surface area as the entire spray.*» However, a physical link between this definition and atomization efficiency is still missing. The formulation in Eq. (5) is the same as Lefebvre [3] and Evers [10], but these authors used a general variable *D* as a representative diameter and then stated that the Sauter mean diameter is the best choice by its definition. However, linking d_{32} with the atomization efficiency implies it is not a choice but an outcome.

Panão et al. [11] explain why choosing a mean diameter in spray characterization is inherent to the nature of the research question. In the case of d_{32}, following the interpretation of Sowa [4], it is the mean diameter of an area-weighted drop size distribution. Therefore, if the change in surface energy is the underlying physical process described by the atomization efficiency, it is reasonable to consider d_{32} as the appropriate characteristic size of droplets in a spray. However, while defining the atomization efficiency in Eq. (5), one notices the appearance of the Sauter mean diameter as a result of the interfacial energy of droplets in a spray, justifying why it is a result, not a choice.

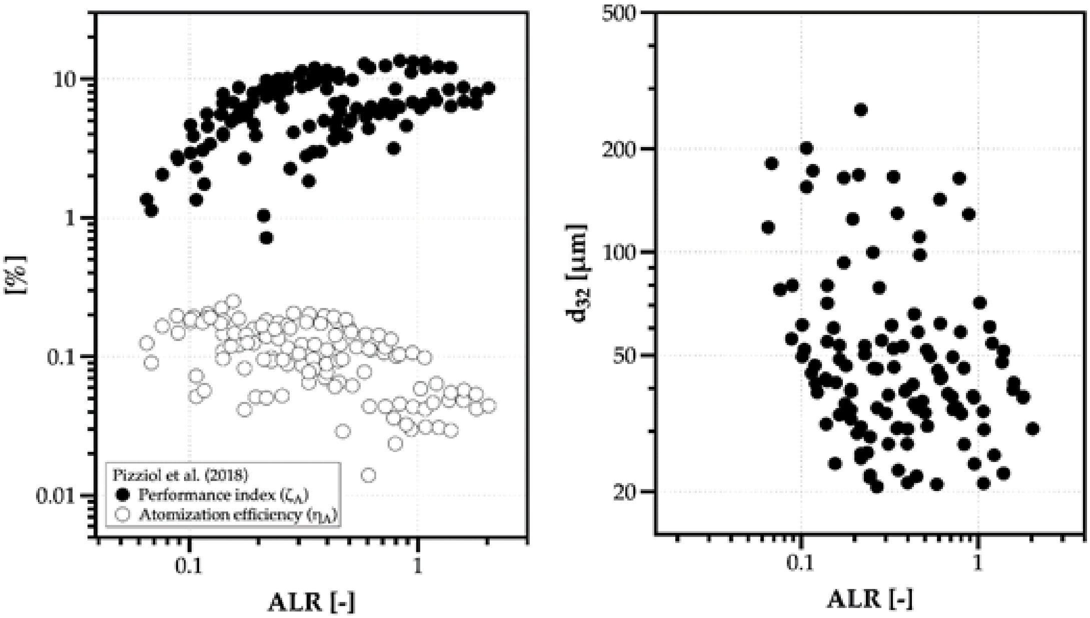

Figure 1: Comparison between atomization efficiency and performance (left); Sauter Mean Diameter as ALR function in Pizziol et al. [7].

Future Directions for the Atomization Efficiency as a Design Tool

Most research works on spray characterization present information on mean drop sizes, especially the Sauter Mean Diameter (SMD), without an apparent reason. Once we establish a physical link between the atomization efficiency and SMD, we aim to develop empirical correlations to predict it, as thoroughly covered in textbooks such as Lefebvre [2]. These empirical correlations include the atomization efficiency, itself correlated with other parameters derived from geometrical features of the atomizer or based on the atomization strategy (e.g., the ALR). However, a mean diameter of a surface-weighted drop size distribution does not enable retrieving any reliable information on the polydispersion of the spray and subsequently measured drop size distributions. The SMD is enough to quantify the atomization efficiency or compare different atomization strategies with similar efficiencies, but predicting the SMD of a spray from the knowledge of the atomization efficiency explains little about its drop size distribution. And without the drop size distribution, it is hard to simulate the spray transport, its footprint if it impacts a surface, and many other applications. Therefore, establishing a link between the atomization efficiency and the original drop size distribution is a topic for future research.

Finally, there is still scarce research on the reasons for such low-efficiency values of liquid atomization. Most new atomization strategies focus on the best way to break up challenging liquids into droplets, for example, considering applications such as sludge drying or the need to produce sprays in small constricted environments. But developing new atomization strategies from the atomization efficiency point of view, paying particular attention to the technology used for the input energy, is also a challenging direction for future research where a proper interpretation of the atomization efficiency is valuable.

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References

1. Jedelsky J, Jicha M (2014) Energy considerations in spraying process of a spill-return pressure-swirl atomizer. Applied Energy 132: 485-495.
2. Lefebvre AH, McDonell VG (2017) Atomization and sprays. CRC press. pp: 300.
3. Lefebvre AH (1992) Energy considerations in twin-fluid atomization. Journal of Engineering for Gas Turbines and Power 114(1992): 89–96.
4. Sowa WA (1992) Interpreting mean drop diameters using distribution moments. Atomization and Sprays 2(1).
5. Shrimpton JS, Yule AJ (1999) Characterisation of charged hydrocarbon sprays for application in combustion systems. Experiments in fluids 26(5): 460-469.
6. Jedelsky J, Jicha M (2013) Energy conversion during effervescent atomization. Fuel 111: 836-844.
7. Xia Y, Khezzar L, Hardalupas Y, Alshehhi M (2019) Influence of Energy Exchange Between Air and Liquid Streams on Spray Characteristics and Atomization Efficiency of Water-Air Impinging Jets. Atomization and Sprays 29(8).

8. Pizziol B, Costa M, Panão MO, Silva A (2018) Multiple impinging jet air-assisted atomization. Experimental Thermal and Fluid Science 96: 303-310.

9. Kowalczuk PB, Drzymala J (2016) Physical meaning of the Sauter mean diameter of spherical particulate matter. Particulate Science and Technology 34(6): 645-647.

10. Evers LW (1994) Analogy between atomization and vaporization based on the conservation of energy. SAE Technical Paper.

11. Panão MO, Moita AS, Moreira AL (2020) On the statistical characterization of sprays. Applied Sciences 10(17): 6122.