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Characterization of a spray generated by an air-blast atomizer

Thesis booklet by

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1 Objective and outline

Gas turbines play an important role in both the energy production and the aerospace industry [1]. Most of them in energy industry work with natural gas, which results in high combustion efficiency and low pollutant emission, compared with other fuels, since it is easy to mix with air. The aim of the process is to ensure homogeneous fuel vapor-air mixture before the flame front. For this reason, properly understanding and improving the quality of atomization a cornerstone in combustion technology. Among the types of atomizers the air-blast one is widely used in engineering practice from painting to metallurgy and from medical applications to gas turbines [2, 3]. In addition to its practical relevance, this type of atomizer is an excellent model platform for studying atomization phenomenon, as the geometry of the atomizer has a relatively low influence on the process of spray formation [4]. The mechanism of liquid atomization is a complex process that involves the transfer of material, energy, and momentum. Due to its chaotic nature, most research is still empirical in this field. The process of atomization can be divided into two main parts, of which the disintegration of the liquid jet is the primary, while the distant fragmentation is called secondary atomization. The complexity of droplet formation is well-illustrated by the fact that only empirical and semi-empirical formulas are available in the literature today to estimate the Sauter Mean Diameter, *SMD* of a spray. However, their number and different study ranges make it difficult to navigate in the area [5]. The individual relationships cannot be applied universally, independently of the atomized material, which is of particular importance when using high-viscosity vegetable oils and fuels.

Figure 1 illustrates the main topic areas covered by the dissertation. Phenomena marked with green border are discussed in the thesis.

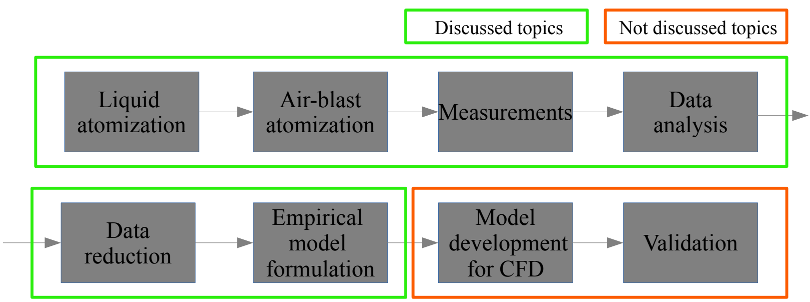

Figure 1: Main steps of the present research.

The general topic is the liquid atomization where the air-blast atomization can be treated as a sub-group. The evaluation of the atomization process can be performed via measurement and data analysis where the enormous measurement data requires proper reduction tools. The final goal is to create new empirical models, which can better fit and could better contribute to the already existing formulas. Finally, these formulas could be integrated into the numerical models in order to improve the quality and then the models can be validated by the measurement results. Here, a plain-jet air-blast atomizer was used for atomizing the investigated liquids, a cross-section of the atomizer shown in Fig. 2.

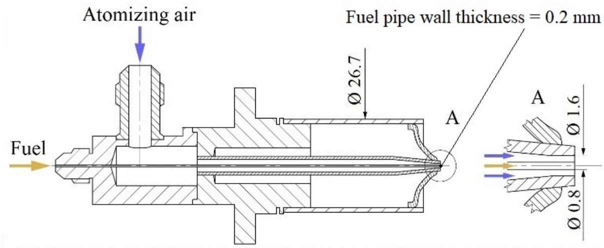

Figure 2: Cross-section of the investigated atomizer.

In the present case, the mixing tube was removed to isolate the atomizer and avoid liquid accumulation on its walls. The liquid flows through a central pipe with 0.4 mm inner diameter while the atomizing air discharges from a concentric annulus of 1.6 mm outer and 0.8 mm inner diameter. This particular atomizer was examined by several other researchers due to its simple geometry and operation [6, 7].

In combustion, viscous liquids require preheating, so the effect of liquid temperature was examined since highly viscous renewable fuels gaining emerging attention. On the other hand, the laser measurement technology has also developed significantly, so it has also become timely to revisit the existing correlations for the *SMD*. Meanwhile, there are also characteristics of the spray that have not yet been published for the air-blast atomizer, such as correlation for the spray half-cone angle. The presentation of this is discussed together with the previously mentioned temperature dependence within the framework of the dissertation.

In addition, *SMD* cannot describe a size distribution alone, hence, probability density functions, PDFs, are also used for evaluation. The currently available literature on the relevant PDFs and their applicability in atomization is highly limited, and their behavior as a function of operating parameters is not discussed [8]. Therefore, the most suitable ones are ranked according to different operating parameters. However, by involving more sophisticated statistical tools such as likelihood analysis, the results can be extended and the droplet size can be better estimated.

2 Methods

The atomization measurements were carried out by using a Phase Doppler Anemometer (PDA) under cold conditions which means that the combustion was not part of the investigations. The PDA is the most suitable measurement system for examining the secondary part of the atomization, as the typical droplet size is in the micrometer range. It can be used to continuously determine the velocity, size and concentration of spherically symmetric particles, droplets, bubbles [9]. Due to the limited availability in Hungary, a series of measurements related to the research were performed at the Technical University of Brno in 2015 and 2017. During the first measurements, the focus was on the atomization of diesel oil (D), where the spray under sub- and supersonic flow conditions was examined. The main objective of the study was to determine the probability density functions (PDF) that provide the best fit for the expected value for distances measured from different nozzles. During the 2017 measurements, the measuring system was expanded with a liquid preheating system, which, in addition to changing the pressure of the atomizing air, also made the viscosity of highly viscous liquids variable by changing the preheating temperature. The test was performed on four different liquids, where distilled water (W) served mainly as a basis for reference measurements. In addition, for preheating, additional measurements were made in connection with diesel (D) atomization, as well as crude rapeseed oil (RO) and light heating oil (LHO). The aim was to evaluate the existing correlations for *SMD*, whether the temperature dependence of the material properties in the original formulas was sufficient or whether additional terms needed to be added to the existing correlations. The spray has already considered as developed from 50 mm axial distance. The experimental atmospheric test rig, which was principally used for the determination of droplet size and velocity, is shown in Fig. 3.

The atomizing gauge pressure values, p_g, were selected based on previous experience from combustion test [10], including both sub- and supersonic regimes in terms of atomizing air discharge velocity. Therefore, the following p_gs were set: 0.3, 0.6, 0.9, 1.2, 1.8, and 2.4 bar. A liquid preheater was also installed in the liquid line, used for all tested liquids. The following preheating temperatures, t_p, were investigated for D, LHO, and RO: 25, 40, 55, 70, and 100 °C. W is an exception since the maximum temperature was 90 °C to avoid boiling, but the lower t_p values were the same as for the other liquids.

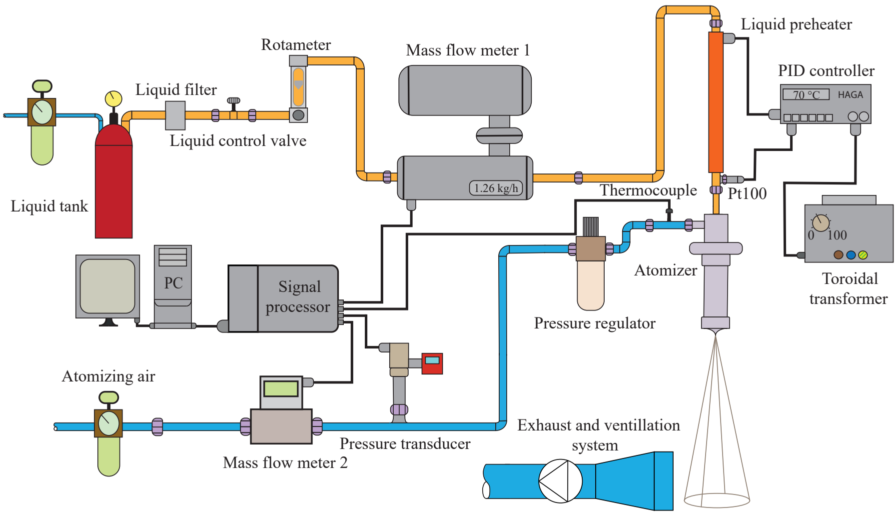

Figure 3: Schematic drawing of measurement rig, featuring piping and instrumentation for the liquid and atomizing air.

Another measurement rig was also developed for spray cone angle, *SCA*, shown in Fig. 4a. The spray was imaged in front of a black plate by a commercial digital camera, and illuminated from the front in a small angle by a LED spotlight, shown in Fig. 4b.

3 Results and theses

Equation (1) is the well-known formula in the atomization literature for estimating *SMD* for a plain-jet air-blast atomizer [5].

$$SMD = d_0 \cdot \left(1 + \frac{1}{ALR}\right) \cdot \left(A \cdot We_{\mathrm{A}}^{C} + B \cdot Oh_{\mathrm{L}}^{E}\right), \tag{1}$$

where d_0 is the initial liquid jet diameter, We_A is the Weber number based on the properties of the atomizing air, Oh_L is the Ohnesorge number based on the liquid properties and ALR is the air-to-liquid mass flow ratio. A, B, C and D are constant. The commonly used values according to the original correlation for C and D are -0.5 and 1, respectively. However, in this formula and other formulas published by other researchers reveals that the effect of viscosity is poorly treated.

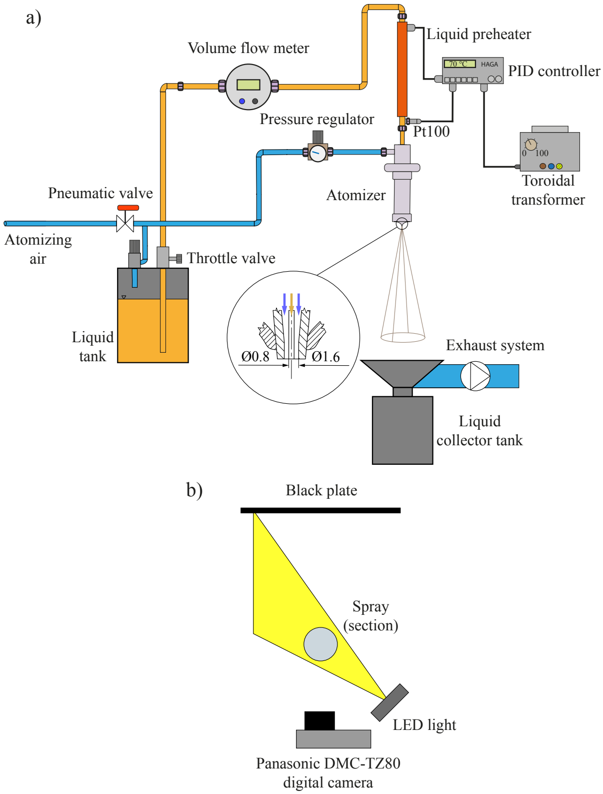

Figure 4: Schematic drawing of a) liquid and atomizing air piping and their corresponding instrumentation, and b) optical setup of *SCA* measurement.

Concluding from the results, it was a general observation, when the liquid viscosity is below a certain viscosity limit, all the already published correlations provide a fair estimation for *SMD*. In addition, the A parameter value remained constant across the entire test range for the low-viscosity liquids. However, in case of high-viscosity liquids, a mostly linear temperature dependence can be recognized. A transition point can be identified via light-heating oil, LHO, especially at $t_p = 70$ °C when further liquid preheating does not affect A. Hence, a phenomenon called as limiting viscosity can be introduced. It means that there is a viscosity value below which any further reduction in liquid viscosity does not affect *SMD* beyond the temperature-dependent material properties already included in the formula, even if the viscosity is further lowered. Therefore, this limit defines a target for the degree of liquid preheating in applications. The limiting viscosity is estimated as $\nu_{\mathrm{L,lim}} = 4.21\ \mathrm{mm^2/s}$ in the present measurement configuration for LHO and is located at 56 °C.

Based on these findings and the measurement data, the following thesis summarizes the contribution of estimating the *SMD* at high-velocity atomization:

1. Thesis

In the case of the air-blast atomization, above the limiting viscosity, $\nu_{\mathrm{L,lim}}$, the We-related term of the Lefebvre's *SMD* correlation becomes temperature-dependent beyond the already included temperature-dependent material properties. The coefficient of Oh also becomes temperature-dependent through the ratio of the viscosity at reference temperature and the viscosity of the preheated liquid. The corresponding reference temperature was 20 °C. The temperature-dependent *SMD* correlation is described as:

$$\frac{SMD}{d_0} = \left(1 + \frac{1}{ALR}\right)\left[A_{t_r} \cdot \begin{cases} \frac{t_p}{t_r}, \text{if } \nu_L > \nu_{\mathrm{L,lim}} \\ 1, \text{if } \nu_{\mathrm{L},t_r} \leqslant \nu_{\mathrm{L,lim}} \\ \frac{(t_p \text{ at } \nu_{\mathrm{L,lim}})}{t_r}, \text{if } \nu_{\mathrm{L}} \leqslant \nu_{\mathrm{L,lim}} \end{cases} \cdot \mathrm{We}_{\mathrm{A}}^{-0.5} + B_{t_r}\left(\frac{\nu_{\mathrm{L},t_r}}{\nu_{\mathrm{L}}}\right)^{0.5} \mathrm{Oh}_{\mathrm{L}}\right],$$

where d_0 is the diameter of the liquid jet and We_A is the Weber number based on the properties of the atomizing air. The validity range is ALR = 0.78 - 2.07, Ma = 0.62 - 1.45, and $t_p = 20-100$ °C for D, LHO, and RO, and $t_p = 20-90$ °C for W. [P1, P6, P7, P8]

Despite the fact that, *SCA* is an easily observable macroscopic feature of the spray, the current scientific literature does not provide a general definition. The correlation between the *SCA* and the operating conditions can be measured, a new correlation can be given. Numerous researchers have dealt with the measurement of *SCA* in the last decades, hence, there are empirical correlations available for several other atomizer types which can be the basis for the correlation development in case of air-blast atomizers [11]. Based on these studies, the geometry of the nozzle, the properties of the liquid, and the density of the surrounding medium have the greatest impact on the *SCA*. According to the preliminary experimental results, the *SCA* is inversely proportional to the power of the atomizing gauge pressure at 10-800 kPa, and no significant change is observable above one MPa [12]. Like pressure, an increase in the density of the ambient medium also increase *SCA*. Nevertheless, other features of the spray, including *SMD*, is influenced by the liquid properties, which are surface tension, viscosity and density. However, in the case of *SCA*, the change in surface tension has no significant effect.

For finding the proper correlation, an image processing algorithm is developed, which included rotation, calibration, cutting, corrections, cleaning and measure the *SCA* in a consistent way. In the corrections part, a threshold algorithm was developed to improve the recognition of not completely sharp spray boundaries. Nevertheless, the ultimate goal of this part was to determine an empirical correlation that adequately estimates *SCA* for air-blast atomization in a wide-range of conditions. By involving several possible independent dimensionless numbers, the half-cone angle as a function of p_g and t_p is determined. Based on the results, the second thesis can be stated:

2. Thesis

The following correlation describes the spray cone angle, *SCA*, which was generated by air-blast atomizer based on the following equation:

$$SCA = A \cdot \tilde{\rho}_L \cdot ALR^B,$$

where $\tilde{\rho}_L$ is the quotient of liquid density at reference temperature and liquid density at the corresponding preheating temperature. *ALR* is the air-to-liquid mass-flow ratio. In addition, two parameters are applied, *A* and *B*. *A* is responsible for describing the corresponding changes in the atomization gauge pressure, while *B* contains the effect of liquid preheating. Parameters *A* and *B* for various liquids are:

	Const.	D	LHO	RO	W
ALR	A	20.7	25.0	25.1	24.3
	B	-0.20	-0.19	-0.18	-0.07

Constant sets for different liquids.

The corresponding equation with constant sets valid at the *ALR* range of 0.78 - 2.07 and Ma range of 0.62 - 1.45. The valid preheating temperature range in case of D, LHO and RO 20 - 85 °C, while in the case of W 20 - 70 °C. [P2, P9]

Nowadays, the statistical analysis of droplet size distribution is increasingly important in practical applications. The main motivation of this part is originated from liquid fuel combustion, where evaporation [13] of a spray affects pollutant emissions [8, 14]. Besides, general-purpose painting, thin-film technologies are rather sensitive to the size distribution of a spray [15]. The goal is to fit and evaluate various probability density functions (PDF), focusing on the highest probability. This method is useful when a characteristic mean droplet size distribution is to be determined, like *SMD*. In the framework of this analysis, two extreme cases were investigated in terms of p_g. Both of them include two downstream distances, which represent the vicinity of the nozzle with ongoing atomization and the developed spray. Following the literature of air-blast atomization, 3 PDF types were highlighted for the qualitative R^2 evaluation. The analysis was extended to other PDF types and many of them provided good result in regards of fitting quality. Finally, it can be concluded that the most commonly used ones in the literature provided the best fit. Nevertheless, four additional PDF types are also suitable for estimating the droplet size distribution of plain-jet air-blast atomization. By combining the results with the other findings in this section, the following thesis can be stated:

3. Thesis

In the case of plain-jet air-blast atomization of diesel oil in the range of 0.3 - 3.1 bar atomization gauge pressure at 25 °C reference liquid temperature the Γ function provide the best fit, followed by the Rosin-Rammler and the Log-normal functions, if an expected value-like parameter is to be determined. PDFs with more degree of freedom than two are not recommended to avoid overfitting. In addition, the PDF has to be positive, continuous, and unimodal. The validity range is ALR = 0.78 - 2.32, Ma = 0.62 - 1.57 and the established sequence is true for low viscosity and high velocity atomization. [P3, P4]

Within the extension of the statistical examination, log-likelihood analysis can be used, which reveals information about the fit quality of various PDFs, focusing on the size distribution, not only to an arbitrary-defined expected value-related term. In this section, 18 PDF types were re-investigated from log-likelihood point of view. Seven PDF types showed superiority over the others which are discussed further. In order to be able to compare the results between each other a performance map methodology was created. The likelihood results were rescaled between 0 and 100, representing the performance of the functions relative to the worst and the best performances, respectively. Relative log-likelihood results were summarized in a color scale table for every

PDF separately. Based on these results, the following scientific contribution can be stated:

4. Thesis

In the case of air-blast atomization, general spray modeling by a single PDF is not possible due to differences in local spray characteristics. Overall, the Burr PDF type is the most suitable one in terms of log-likelihood, appropriately modeling the spray at both the core and the less regular peripheral region. However, when the core regions of the spray are investigated at 0.6 bar atomizing gauge pressure, the Generalized Extreme Value PDF type provides outstanding fit quality. Considering the two-parameter PDF types only, Nakagami can be treated as the best choice for all the investigated conditions. The popular Rosin-Rammler PDF in the atomization literature was notably outperformed by other PDF types. The validity range is ALR = 0.78 - 2.07 and Ma = 0.62 - 1.45. The valid preheating temperature range in case of D, LHO and RO 20 - 100 °C, while in the case of W 20 - 90 °C. [P5]

4 Application of the results

Plain-jet air-blast atomizer is widely used in engineering practice from painting to metallurgy and from medical applications to gas turbines. In addition to its practical relevance, this type of atomizer is an excellent model platform for the study of atomization phenomenon, as the geometry of the atomizer has a relatively small effect on the spray formation. Furthermore, this type of atomizer is widely used due to their simple geometry, low manufacturing cost, and easy maintenance. The process is mostly studied in measurable way due to its chaotic nature. Therefore, the main focus in the present thesis was to develop novel and advance existing tools for engineers dealing with atomization.

The previously introduced result largely focus on experimental techniques, thence, the concluded results can be directly implemented into similar plain-jet air-blast atomizers to the investigated one. Besides, the comprehensive analysis pave a way for numerical model refinement to facilitate cost-effective solutions for engineers. The investigated liquids were selected to represent a wide range of material properties, which can be treated as model liquids for different kind of combustion applications.

By implementing the globally descriptive correlations into finite volume-based simulation models, then the complex process of the atomization can be further investigated.

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