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Effervescent Spray Modelling: Investigation of Drop Momentum Models and Validation by Measured Data

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The use of effervescent atomizers is constantly rising and therefore the need to develop and validate appropriate models is increasing as well. The main goal of this paper is to investigate an effervescent spray model for combustion simulations. In the first part of the paper is described the spray measurement experiment along with the used measuring techniques. In the second part Euler/Lagrange approach is adopted for the two-phase flow simulations and the selected models for primary and secondary breakup, droplet drag and collisions are briefly described. Primary and secondary atomization is evaluated in a computational isothermal spray experiment. Results show discrepancies in the prediction of radial evolution of Sauter mean diameter (SMD). Difficulties in predicting the formation of small drops are highlighted.

1. Introduction

In the field of spray combustion, especially in oil furnaces and combustors, effervescent atomizers (twin fluid atomizers with internal mixing) are quickly gaining on popularity over more traditional forms of atomization. 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 (usually air) is introduced in the liquid before it exits the atomizer and a two phase flow is formed (Jedelský et al., 2007). When the mixture exits through the nozzle, the pressure drop forces the gas bubbles to expand causing the liquid to break up. This breakup mechanism allows the use of lower injection pressures and larger nozzle diameters without compromising the drop-size distribution (Babinsky and Sojka, 2002). In general, the atomization process is divided into primary and secondary breakup. The primary breakup occurs when the fluid flow exits the orifice and besides being dependent on properties of the fluids involved, it is also strongly dependent on the atomizer type, its inner structure and geometry. Secondary atomization is a process during which droplets further break up or collide leading to various outcomes (reflection, coalescence, breakup, etc.). Unlike primary atomization, secondary atomization depends only on properties of the atomized liquid (viscosity, velocity, temperature, surface tension, density, etc.) and of the surrounding fluid, typically air (Lefebvre, 1989).

In the last few decades CFD tools have been employed to facilitate the combustor designs (Jordan et al., 2010; Broukal and Hájek, 2010). For the majority of industrial applications it is prohibitively expensive to model the two-phase flow inside the

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atomizer (this would imply the use of Euler/Euler approach), therefore only external flow is modelled by the Euler/Lagrange approach. In this case the gas phase is modelled as a continuum but the liquid phase is treated as a system of discrete particles (droplets) that are tracked in the gas flow field. It is therefore necessary to use appropriate models for primary and secondary. A great variety of models for both primary and secondary breakup have been investigated by many researchers (Calay and Holdo, 2008; Park and Heister, 2010; Qian et al., 2009; Xiong et al., 2009; Yan et al., 2008; Broukal et al., 2010).

The method adopted in the present work is based on the Euler/Lagrange approach, coupled with Lund's model (Lund et al., 1993) to account for primary breakup. Lund's model and its variations are often adopted due to its simplicity and satisfactory predictions (Xiong et al., 2009; Schröder et al., 2010). The secondary breakup is then governed by Reitz's wave model (Reitz, 1987).

2. Data Analysis and Experiments

The measured spray of extra-light fuel-oil was generated using the effervescent atomizer and operating conditions described in (Jedelský et al., 2009) as configuration E38. Drop sizes and drop velocities were measured using a Dantec phase/Doppler particle analyzer (P/DPA) in 6 radially equidistant sampling points at 150 mm from the atomizer orifice. The angle depicted in Figure 1 represented the spray half-angle and was estimated as the angle between the axis and the farthermost measurement point. A detailed description of the measurement can be found in (Jedelský et al., 2009).

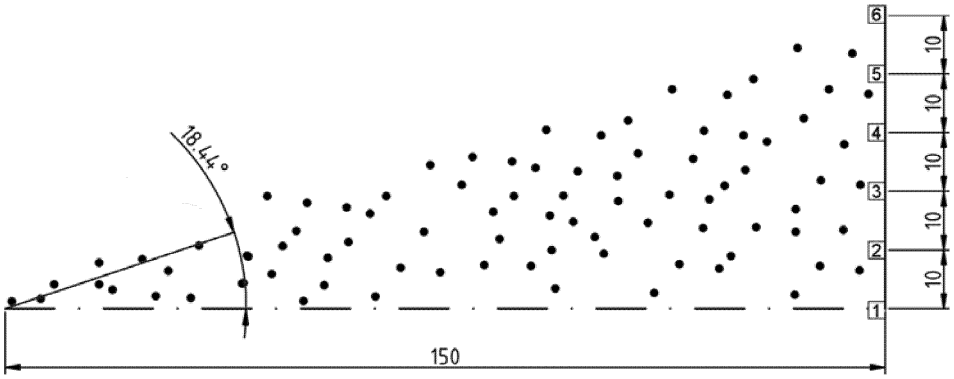

Figure 1: Schematics of the spray measurement

3. Modelling

This section presents the models applied in the computational part. The modelling work consists in a validation of the primary and secondary atomization model in a setup that mimics conditions during the spray measurements. The computations were performed in Ansys Fluent code (Ansys Fluent, 2009). To track the liquid particles Discrete Phase model (DPM) has been used, which is based on the Euler/Lagrange approach. The

particles were tracked in an unsteady fashion. To predict the particle trajectory, one has to integrate the force-balance equation, which can be written (for the x direction in Cartesian coordinates) as follows:

$$du_p/dt = F_D\left(u - u_p\right) + g_x\left(\rho_l - \rho_g\right)/\rho_l, \tag{1}$$

where u_p is the particle velocity, u the surrounding air flow velocity, g_x gravity in x direction, ρ_l and ρ_g are the densities of the liquid and gaseous phase. $F_D(u- u_p)$ is the drag force per unit particle mass.

$$F_D = 18\mu_g C_D Re_{rel}/\left(24\rho_l d^2\right), \tag{2}$$

where d is drop diameter, μ_g is the molecular viscosity of the fluid (air), C_D is the drag coefficient and Re_{rel} is the relative Reynolds number defined as $Re_{rel} = \rho d_p\left|u_p - u\right|/u_g$.

3.1 Spray model

Ansys Fluent offers a variety of atomizer models and injections. Unfortunately, it does not offer any atomizer model that corresponds to the atomizer used in the experiments; therefore it was decided to use a so-called solid cone injection instead. The spray is symmetrical and therefore, to reduce computational costs, only a 30° cylinder section has been meshed using 15,720 hexahedral cells. The spray was injected from a small circular area of diameter 2.5 mm representing the actual nozzle orifice. In the position of measuring location 150 mm downstream from the injection a series of concentric annular control surfaces have been set up that enabled the virtual measurement of droplets. A small air co-flow (0.5 m/s) was introduced to improve solution stability, periodic boundary condition was enforced on the sides of the 30° cylinder section in order to obtain meaningful results for the whole cylinder and finally a pressure outlet condition was used for flow exit. For the sake of simplicity, gravity was ignored.

Primary breakup

In this work, a one-dimensional breakup model based on Lund (Lund et al., 1993) and further developed in (Xiong et al., 2009) is used to predict the spray SMD after primary breakup. The model assumes that the annular liquid sheet breaks into several cylindrical filaments with almost the same diameter as the thickness of the annular sheet. The filaments then break into ligament fragments at the wavelength of the most rapidly growing wave and each fragment only forms one drop. The predicted SMD is later used as the initial diameter of injected droplets during the numerical simulation. The initial particle velocity was approximated using a formula derived by Jedelský and Sláma in Appendix 2 of (Jedelský et al., 2009) and the spray angle was determined from the experimental measurement.

Secondary breakup

Secondary breakup was taken into account by including the wave model by Reitz (Reitz, 1987). This model was developed for high-Weber-number flows and considers the breakup to be induced by the relative velocity between the gas and liquid phases. The model assumes that the time of breakup and the resulting droplet size are related to the fastest-growing Kelvin-Helmholtz instability. The wavelength and growth rate of

this instability are used to predict details of the newly-formed droplets. This model requires two parameters. The first parameter (C_1) affects the radius of the child droplets and has been set to 0.61 based on the work of Reitz (Reitz, 1987). The breakup time scale is governed by the second parameter (C_2), which can range from 1 to 60 depending on the spray characteristics. The parameter C_2 is a measure of how quickly the parent droplet will lose mass. In their work (Liu et al., 1993) recommended 1.73 as a default value. In this work, together with the default value, two other values are tested, namely 2.5 and 10.

Droplet drag and collision models

Accurate determination of droplet drag coefficients is crucial for accurate spray modelling. Ansys Fluent provides a method that determines the droplet drag coefficient dynamically, accounting for variations in the droplet shape. The shape of drops is often assumed to be spherical, but in the case of high Weber numbers, this assumption can distort the final results. The dynamic drag model accounts for the effects of droplet distortion, linearly varying the drag between that of a sphere and a value of 1.54 corresponding to a disk. The algorithm of O'Rourke (O'Rourke, 1981) was used to determine the outcome of drop collisions.

4. Results and Discussion

The initial droplet diameter predicted by the primary atomization model was 225.2 μm. The data on the resulting numerical spray were collected in a similar manner as in the experiment.

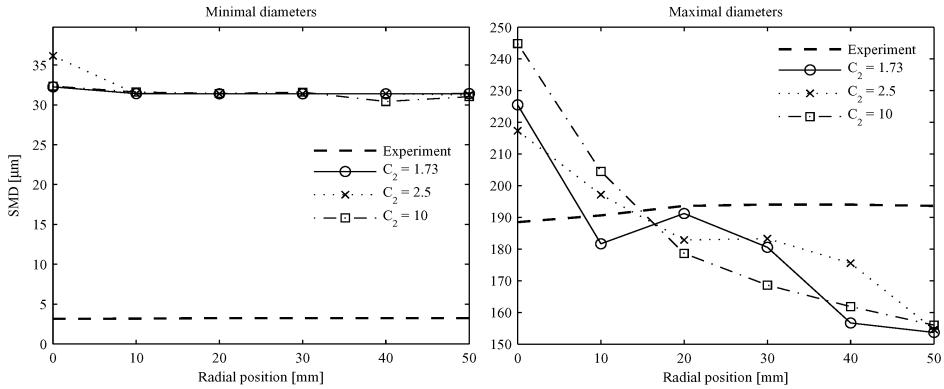

Figure 2: Minimal and maximal drop diameters

From *Figure 2* it is apparent that the model in all three cases fails to predict drop diameters smaller than approximately 31 μm and on the other hand the maximal predicted diameter is greater (245 μm) than the maximal experimentally measured diameter (194 μm). This is probably caused by the wave model, which does not predict any breakup at lower Weber numbers and therefore in the remoter spray regions the drop diameter increases due to coalescence. Also, for all three cases the maximal

diameter decreases while moving to the spray peripheral region, which is not observed in the experiments.

The overall SMD obtained from simulations (67.6 μm) under predicts the experimental value (83.2 μm). This mismatch is opposite than the one reported in (Schröder et al., 2010), where the simulated SMD exceeded experimental SMD. The radial evolution of predicted and measured SMD is shown in Figure 3. The experimental measurement shows that SMD is smallest at the spray core and then increases when moving to the edge of the spray. The predicted SMD evolution is however different.

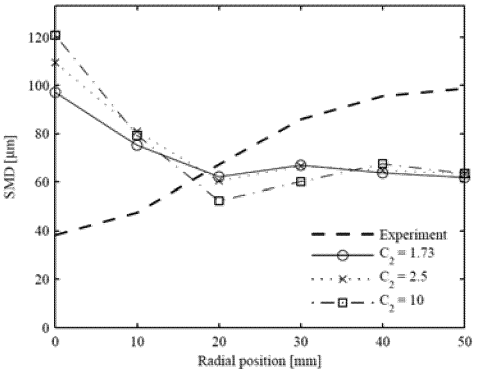

Figure 3 Comparison of measured and computed radial SMD evolution

At the spray core the biggest SMD value is predicted and SMD further decreases. After the third measurement point it remains almost constant. This discrepancy clearly shows the poor prediction of radial spray drop-size distribution regardless of the C_2 parameter value.

5. Conclusion and Future Work

In this study an effervescent spray model based on commonly used primary and secondary breakup models was investigated. SMD evolutions for three cases differing by the value of C_2 parameter in Reitz's secondary breakup model have been compared with experimental data. The results show that minimal and maximal predicted diameters differ from experimental values. This is most probably caused by trade-offs in the secondary atomization model, as discussed in Section 3.1. Furthermore it has been shown that the spray model does not predict well radial changes in SMD disregarding the C_2 parameter. This points to a deeper discrepancy which is to be found probably in the primary atomization model. More experimental data would be needed in order to compare the proposed model in terms of axial SMD evolution.

In the oncoming research emphasis will be placed on improvement of the proposed spray model. Velocity and mass flow rate distributions in the primary breakup model will be examined as well as their effect on the resulting drop-size distribution and consequently on wall heat fluxes in combustion applications.

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