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Multi-step spray modelling of a flat fan atomizer

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ABSTRACT

The present study combines Eulerian CFD modeling of the liquid flow inside an atomizer, instability analysis of liquid sheet, statistical spray analysis, and Lagrangian modeling for spray transport of a flat fan atomizer widely used in agricultural spraying. High-speed spray imaging and spray size measurements carried out for validation of numerical models and the experimental results agreed reasonably with the modeling results. Although the subject of the study is a flat fan atomizer, the methodology presented could be employed to other types of spray nozzles that rely on liquid sheet disintegration mechanism. The systematic modeling of spray systems with the methodology explained in the paper not only reduces the design and prototyping time and costs but also gives engineers a better understanding of the design parameters for improved spray system performance.

1. Introduction

There are many kinds of spray atomizers for different applications. However, they all essentially convert an external energy source to liquid surface energy for increasing the rate of heat and mass transfer by forming multiplicity of droplets.

Although a spray may contains droplets with widely varying range of sizes and velocities, many applications have specific or sometimes very strict spray requirements or need to control spray dynamics to work efficiently. For instance, in nasal drug administration to ensure successful deposition within the nasal cavities, droplet sizes between 30 and 120 µm are desired, for example see Copley and Kippax (2012). While droplets larger than 120 µm deposit at the front of the nose, the finer ones are inhaled and reaches the lungs that may cause safety issues and should be avoided, see Kulkarni and Shaw (2012) and Sangolkar et al. (2012). In mass spectrometry applications with inductively coupled plasma (ICP-MS) droplets larger than 10 µm do not undergo complete vaporization in the plasma torch and may not contribute into signal, see Montaser and Golightly (1992). In addition to this size restriction, droplets must fall below a certain velocity to have enough residence time in the plasma torch for total consumption. Therefore, to control spray flow to the plasma torch and achieve reasonable efficiency in ICP-MS, spray chambers are used to filter large and fast moving droplets.

In agricultural applications, spray droplet size also plays a crucial role in aerial or ground spraying of crop protection products and fertilizers. Undesired pesticide or fertilizer deposition is likely to occur if spray is not within a certain size range, see Liu (2000). Production of very small droplets is undesirable as they drift and result in environmental contamination and waste of pesticide. While pesticide particles carried by air currents may injure people, the most frequent claim for damages is drift from an herbicide that is carried onto nontarget agricultural crops, see Cetner (2014). Accuracy of spraying is also a very important issue in controlling the drifting of sprayed pesticides. Herbicides such as dicamba and 2,4-D should not reach non-GMO varieties of soybeans or cotton which from past experience are known to be highly sensitive to low-dose exposures of these agents, Egan et al. (2014).

The above examples show the importance of spray characteristics for different applications. Atomizing nozzles must therefore be designed with great care to fulfill the design criteria for their intended application. Since the manufacturing process is often very lengthy and prototyping cost in designing a nozzle could be substantial, it would be very helpful to employ numerical tools to help speed up the process. There have been many attempts to model the atomization and spray in the past and the mechanism of the breakup has been studied in details, for example see Liu (2000). For instance in a recent study, Xue et al. (2014) used volume of fluid (VOF) method to integrate the internal nozzle flow and the developing fuel spray. Zhou et al. (1996) employed CFD to relate the spray angle of a flat fan atomizer to its internal geometry. As another example, Altimira et al. (2009) studied influence of the nozzle geometry on the flow as well as formation and development of liquid sheet by numerical modeling. Their model was able to predict the discharge coefficient and the liquid sheet thickness of a fan spray atomizer and validated by experimental measurements.

However, despite great advances in the computational fluid

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dynamics, simulating atomization still remains a challenging task. One reason is that in primary spray atomization, there are different dimensions involved. A nozzle with dimensions in the order of few millimeters could generate a sheet with thickness as low as few micrometers disintegrating into many droplets which could travel some decimeters downstream of the nozzle. Obviously modeling a system with such a wide range of length scales is numerically challenging.

In this paper, we present an approach for the prediction of spray characteristics that combines several sub-models to accurately predict spray dynamics for an actual application. First, we employ an Eulerian based model to simulate the liquid flow inside the atomizing nozzle, its evolution and spreading as it exits the tip of the nozzle to form a thin liquid sheet before the primary breakup occurs. The data gathered such as sheet spreading angle, surface area, thickness and velocity from the Eulerian sub-model is then fed into an analytical model to find average quantities such as mass mean diameter. The results of Eulerian and analytical sub-models are then used as input for the statistical sub model to predict joint size and velocity distributions which in turn are used as input in a Lagrangian sub-model to simulate spray transport.

We modeled a flat-fan spray nozzle that is used for spraying herbicide, fungicide and insecticide. This class of atomizers produces a wide spray angle and is well suited for field sprayers equipped with sprayer controllers.

2. Experiments

An experimental setup was prepared to characterize the flat nozzle. This spray nozzle falls into the category of flat-fan atomizers which are capable of producing wide spray angles (typically over 100 degrees) and provide a good spray distribution over the pressure range of 15–60 psig (1–4 bar).

The setup was used for spray imaging to extract experimental data such as spray angle and liquid sheet breakup length. The spray size measurement was also performed using D_{30} Spray Sizer by Coraltec Inc. (US Patent # 20140355008 - 2014). The schematic of the experimental rig is shown in Fig. 1.

As recommended by the manufacturer, the nominal measurements for the spray angle are done at 40 psig and 1.14 l/min. We chose flow rates above and below this nominal value to observe the effect of the flow conditions on the spray angle, sheet thickness and droplet size measurement. In our experiments water was sprayed at two operating conditions:

- High flow rate (pressure = 48 psig (3.3 bar)/measured flow rate = 1.2 l/min)
- Low flow rate (pressure = 24 psig (1.7 bar)/measured flow rate = 0.8 l/min)

For each case the images of the spray were obtained using a high speed camera (Photron Fastcam SA5) at a rate of 50,000 frames per second (fps) and utilizing a light source radiating through the liquid water sheet in order to capture the ligament formation of the spray. The results of spray imaging will be presented in the next sections alongside numerical results for comparison.

The size measurements were taken by D_{30} Spray Sizer. This technology measures volumetric droplet size, i.e. D_{30}, of the spray by collecting specific amount of liquid and counting the number of droplets passing a laser beam probe. The Spray Sizer does not offer size distribution and no information regarding spray velocity. However the device is suitable for quick spray analysis since it is very inexpensive, does not have large number of instruments and requires very little calibration and user expertise in comparison to much sophisticated measurement technologies such as Phase Doppler Particle Analyzers. The results of spray size measurements will be presented and used in the upcoming sections.

3. Eulerian Sub-model

For the Eulerian sub-model, we employed the SimSpray software suite by Simulent Inc. SimSpray flow solver has been used to study a wide range of industrial spray nozzles, e.g. pressure swirl and splash-plate atomizers, see Fard et al. (2002, 2007) and Levesque et al. (2005).

SimSpray employs a two-step projection, Eulerian fixed-grid method to solve the Navier-Stokes equations. The interface is resolved by the volume-of-fluid (VOF) method (Bussman, 2000). The flow is assumed to be single phase, laminar, incompressible, and Newtonian. The assumption of a single phase fluid is reasonable and will reduce the computational efforts significantly, since the ambient air is stationary. The software can model the flow field inside the nozzle, its spread downstream of the nozzle, the formation of a liquid sheet, and sheet break-up into fine droplets. However, this approach is computationally expensive. In addition, because resolving the sheet breakup numerically is somewhat mesh dependent, one should carry out an extensive set of simulations to ensure that modeling results are reasonably mesh independent. An alternative approach, which is taken in this study, is to simulate the flow filed to an extent smaller than the breakup length and extract useful information (sheet thickness, velocity, etc.) which will be used by other modeling tools to predict sheet break-up.

The spray nozzle consists of two parts, a metal core that is the main part of the spray nozzle and a plastic jacket holding the metal core which is also used for mounting the nozzle on the spraying systems. Since the plastic part does not interfere with the spray coming out of the nozzle tip, it was excluded from the numerical modeling As can be seen from Fig. 2a, b the fluid enters the nozzle from a circular section (Ø4.65 ± 0.02 mm × 3.50 mm) and is then directed to a smaller section (Ø1.65 ± 0.02 mm × 2.50 mm) that ends to a semi-sphere dome.

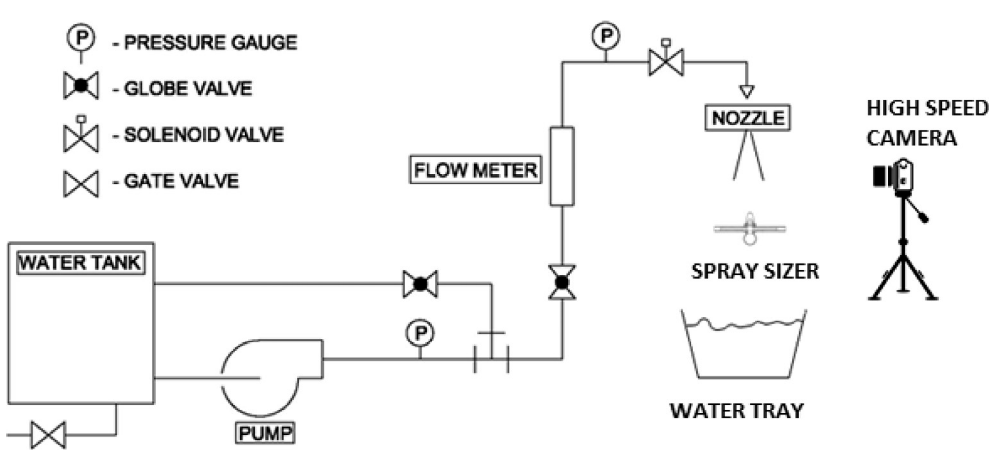

Fig. 1. Schematic of the setup used for spray imaging and size measurement.