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Flow characteristics and turbulence analysis of a large-scale pressure-atomized spray

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A typical water round-nozzle jet for agricultural applications is presented in this study. The dispersion of a liquid for irrigation or pesticides spraying is a key subject to reduce both water consumption and air pollution. A simplified study case is constructed to tackle both scenarios, where a round $d_n = 1.2\text{mm}$ nozzle of a length $L_n = 50d_n$ is considered. The water injection bulk velocity is equal to $U_j = 35\text{m/s}$, aligned with gravity, placing the liquid jet in a turbulent atomization regime. Experimental and numerical approaches are considered.

LDV and DTV optical techniques are used to gather statistical information from both the liquid and the gas phases of the spray. The experimental campaign is carried out from $x/d_n = 0$ to 800. Concerning the LDV, small ($\sim 1\mu\text{m}$) olive-oil tracers are used to capture the gas phase, where a distinction between the liquid droplets and tracers is achieved by a specific set-up of the laser power source and the burst Doppler setting (BP-Filter and SNR). On the dispersed zone, DTV measurements are carried out to determine velocities and sizes of droplets. Special attention to the depth-of-field (DOF) estimation is taken in order to obtain a less biased droplet's size-velocity correlation. Finally, an optical probe (OP) was also used to determine the liquid volume fraction \bar{Y} , liquid mass fraction \tilde{Y} , and mixture density $\bar{\rho}$, which are important features for such flows. These are key quantities for the determination of the mixture mean velocities and Reynolds stresses, and evaluation of the terms in their balance equations. Combining OP, LDV and DTV data allows to determine quantities such as the mixture mean density, $\bar{\rho} = \bar{Y}\rho_L + (1 - \bar{Y})\rho_G$, mixture mean velocity along the i direction, $\tilde{u}_i = \tilde{Y}\tilde{u}_{i,L} + (1 - \tilde{Y})\tilde{u}_{i,G}$, or mean slip velocity, $\bar{u}_{i,S} = \bar{u}_{i,L} - \bar{u}_{i,G} = \frac{\overline{u_i''Y''}}{\bar{Y}(1-\bar{Y})}$, where the notation '' denotes fluctuations with respect to the Favre averaged mean values. Similar relations hold for the Reynolds stresses.

For such a flow, three dimensionless quantities can be constructed as a function of the forces that intervene in the atomization process. First, the nozzle Reynolds number, $Re = \frac{U_j d_n}{\nu_L}$, allows to identify if the liquid flow inside the injector is turbulent. Then, the liquid Weber number, $We_L = \frac{\rho_L U_j^2 d_n}{\sigma}$, and the gas Weber number, $We_G = \frac{\rho_G U_j^2 d_n}{\sigma}$, which weights the importance of surface tension once the flow is in contact with the surrounding air. Finally, the Ohnesorge number, $Oh = \frac{\rho_L \nu_L}{\sqrt{\rho_L \sigma d_n}}$, characterizes the form of the liquid packets or droplets in the atomization process. Choosing $Re = 41833$ and $L_n/d_n = 50$ makes the internal flow fully turbulent and ensures that the boundary layer inside the nozzle is fully developed for any upstream conditions. With $We_L = 20158$, $We_G = 24.3$ and $Oh = 0.0034$, the liquid phase turbulent kinetic energy should be the main responsible of the liquid-jet primary break-up, these flow conditions lying within the second wind-induced atomization regime.

An Eulerian mixture multiphase model was also implemented to describe the original two-phase flow. Several U-RANS turbulence models are used: $k-\epsilon$ and RSM; where special attention is taken to the modelling of variable density effects from the mixture formulation. A custom numerical solver is implemented using the OpenFOAM CFD code. A series of study cases are constructed to test the influence of the turbulence modeling and first/second-order closures of the turbulent mass fluxes.

Figure 1 reports radial profiles for the mean liquid mass fraction \tilde{Y} and longitudinal and radial velocities at $x/d_n=600$, where the liquid core has disappeared. As expected, the liquid-phase velocities are significantly larger than the gas-phase ones. In addition, because of the definition of the Favre-averaged mixture velocity \tilde{u}_i , the contribution from the liquid phase to the mixture velocity becomes negligible from the radial position where \tilde{Y} is smaller than about 0.2, while it is largely dominant as long as \tilde{Y} is larger than about 0.6.

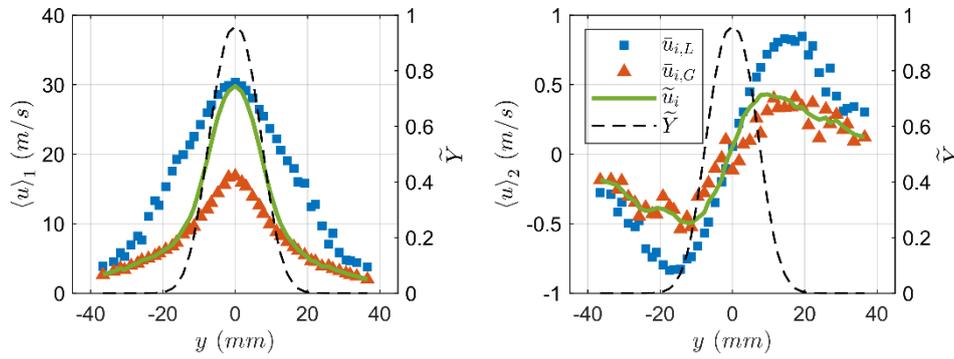


Figure 1. Mean liquid mass fraction \tilde{Y} and longitudinal $\langle u \rangle_1$ (left) and radial $\langle u \rangle_2$ (right) velocities at $x/d_n=600$.

Droplet mean velocities $\bar{u}_{i,(k)}$ and Reynolds stresses $\bar{R}_{ij,(k)}$ by size class (k) are reported in Figure 2 at the same position, $x/d_n=600$. Three distinct behaviors can be observed, for droplet sizes larger than about 300 μm , those smaller than about 50 μm and those in between. In particular, the streamwise velocity is almost the same for the largest droplets and its longitudinal evolution is very slow. For this class of droplets, the Reynolds stresses are very small. This class of droplets is mostly dominated by inertial effects, and the associated Stokes numbers¹ $St(k)$ are about 100 or more (see Felis, 2017). On the contrary, the smallest droplets tend to mix very quickly with the gas phase, with a much weaker mean velocity and Reynolds stresses R_{11} and R_{22} which have much larger values, with the maxima located on the jet axis. For these droplets, inertial effects are almost negligible, and Stokes numbers are between 5 and 1. For the intermediate range of sizes, there is a continuous evolution from the largest to the smallest class behavior, with R_{11} progressively increasing from the sides of the jet - where velocities are smaller - to the jet axis.

Numerical results for the mixture properties are in general good agreement with the experimental data, and especially for the mean velocities, \tilde{Y} values and Reynolds stresses, even though, in the near field region (where the liquid core still exists), discrepancies are larger. Such results will be presented and discussed during the conference.

¹ For a class k, associated to a mean diameter $d_{(30,k)}$, $St(k)$ is defined by $St(k) = \frac{\tau_R}{\tau_t} = \frac{\rho_L d_{(30,k)}^2}{18\mu_G \left(1 + 0.15Re_{d_{(30,k)}}^{0.687}\right)} \frac{y_{0.5\tilde{u}}}{\sqrt{R_{11,G}}}$

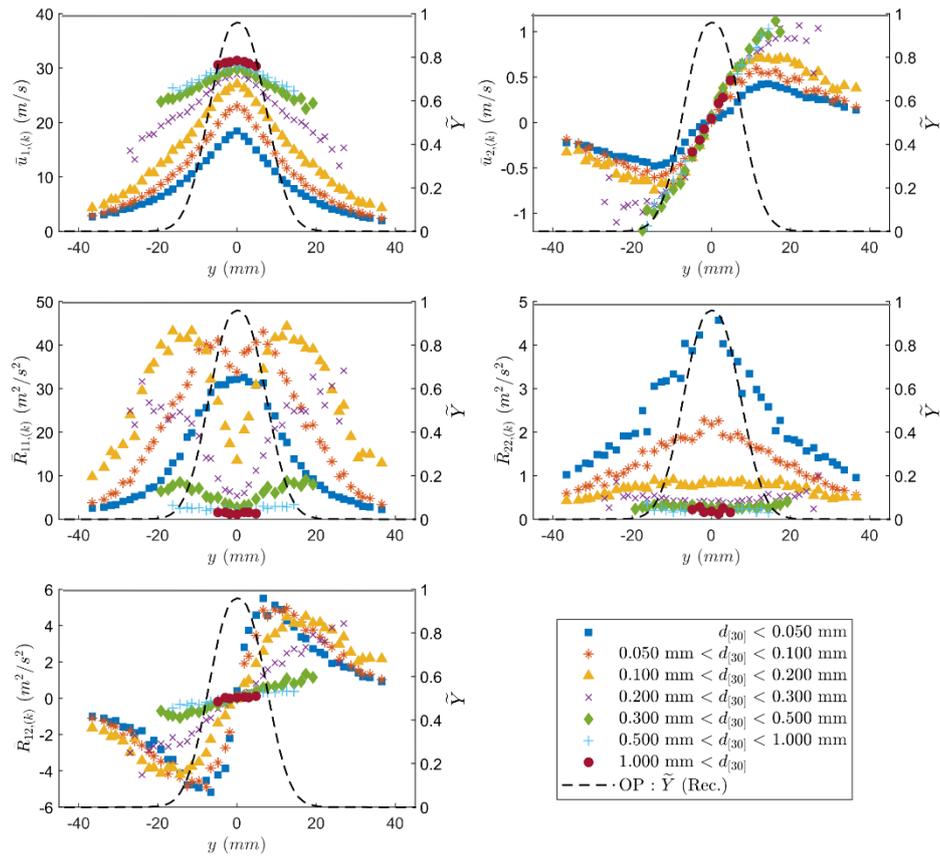


Figure 2. Droplet mean velocities $\bar{u}_{i,(k)}$ (top row) and Reynolds stresses $\bar{R}_{ij,(k)}$ by size class (k) at $x/d_n=600$.

FELIS F., Atomization and dispersion of a liquid jet: numerical and experimental approaches, Ph D Thesis, IRPHE-IRSTEA, Ecole Centrale Marseille (2017).