IN-VENTO 2026
International Conference of the Italian Association for Wind Engineering
Bari, September 13th – 16th, 2026

BARI

Liquid jet in gaseous crossflow for agro-robotic applications

Germán Vázquez[1], Ignacio Franco[2], Mercedes Marzoa[3]

[1]*Udelar, Facultad de Ingeniería, IMFIA, Montevideo, Uruguay, gvazquez@fing.edu.uy*
[2]*Udelar, Facultad de Ingeniería, IMFIA, Montevideo, Uruguay, ifranco@fing.edu.uy*
[3]*Udelar, Facultad de Ingeniería, INCO, Montevideo, Uruguay, mmarzoa@fing.edu.uy*

SUMMARY
This project presents an experimental investigation of vertically injected liquid jets in gaseous crossflows. Wind tunnel experiments have been conducted within a range of gas Weber numbers (We_g) and momentum ratios (q) relevant to precision agriculture applications, covering parameter spaces that remain scarcely explored in the literature. High-resolution video data is being processed using a Python-based digital image analysis framework (OpenCV), enabling color segmentation, morphological filtering, and temporal spatial accumulation to reconstruct mean jet penetration trajectories. Empirical fitting curves are currently under development, and comparison with existing correlations is planned as a subsequent stage of the project.

Keywords: Liquid Jet in Gaseous Crossflow, Agricultural Robotics, Wind Tunnel Validation, Vertical Injection.

1. INTRODUCTION

In (Rouaix et al., 2023)(Yoon et al., 2011)(Inamura et al., 2000)(Wu et al., 1997), an extensive review of the existing literature on liquid jets in gaseous crossflows (LJGC) is presented, including a comprehensive map of studied conditions in terms of gaseous Weber number (We_g) and momentum flux ratio (q). This compilation reveals a clear lack of experimental data in the low-We_g, high-q regime, particularly for small jet diameters and low crossflow velocities, which are representative of precision agriculture applications.

The present work specifically addresses this gap by focusing on the characterization of the mean jet trajectory under these conditions. This study constitutes a first stage, to be followed by a more comprehensive experimental campaign that will incorporate additional parameters, such as non-vertical injection angles, to better represent realistic operating conditions.

Our project is a collaboration led by the Association of Fruit Growers of Integrated Production (AFRUPI) and supported by the Ministry of Livestock, Agriculture, and Fisheries (MGAP/DIGEGRA), the National Institute of Agricultural Research (INIA), and GTZ (Deutsche Gesellschaft für Internationale Zusammenarbeit). The initiative aims to advance sustainable fruit farming in Uruguay by incorporating innovative agro-technologies. Our research team, primarily from the Institute of Fluid Mechanics and Environmental Engineering (IMFIA) at the University of the Republic, has developed a liquid spraying system designed to reduce herbicide use while minimising environmental impact, ensuring effective and eco-friendly weed management.

2. METHODOLOGY

Key parameters identified in the literature for determining the trajectory of the liquid column include the momentum flux ratio q that compares liquid momentum with gas momentum

$$q = \frac{\rho_j v_j^2}{\rho_g v_g^2} \tag{1}$$

and the gas Weber number We_g, that compares gas momentum to capillary effect

$$We_g = \frac{\rho_g v_g^2 d_j}{\sigma} \tag{2}$$

Where ϱ_j and v_j are the liquid density and velocity, respectively, and ϱ_g and v_g the density and velocity of the gaseous fluid. Finally d_j is the initial liquid jet diameter, and σ the surface tension which takes into account the capillary effects.

Wind velocities ranged from 1.3 to 5.1 m/s, measured using a calibrated Pitot tube referenced to the jet position, representative of low-altitude conditions (≈1 m above ground). Liquid flow rate was measured with a calibrated Arduino YF-S401 flowmeter. Two nozzle diameters were considered: 2.5 mm and 3.8 mm, using a DC centrifugal pump typically employed in automotive windshield washer systems.

All experiments were conducted in the wind tunnel of the Faculty of Engineering, Universidad de la República (IMFIA). High-resolution video recordings were obtained using a high-speed camera and controlled lighting conditions, as illustrated in Figure 1.

High-resolution recordings for each experimental condition were processed using a Python-based framework developed with OpenCV. The procedure consists of: (i) spatial cropping to remove non-relevant regions, (ii) color-based segmentation in HSV space to isolate the liquid phase, (iii) morphological filtering to reduce noise and enforce spatial coherence, and (iv) frame-by-frame accumulation of binary detections to reconstruct the time-averaged jet structure.

3. RESULTS

The resulting accumulated detection matrix represents the spatial probability distribution of the liquid phase, enabling identification of regions where the liquid phase is consistently present, as well as zones of intermittent occurrence. High accumulated values indicate stable jet presence, whereas lower values (e.g., below 75%) reveal fluctuations in jet position, which can be associated with the onset of breakup or unsteady jet behavior.

Figure 1. Experimental setup and image calibration procedure. (Left) Wind tunnel configuration showing the jet injection system, high-speed camera, lighting arrangement, and leveled calibration checkerboard used to establish the pixel-to-millimeter conversion. (Right) Raw image from the camera view, showing where the checkerboard pattern is automatically detected using OpenCV for spatial calibration.

Figure 2 shows an example of the accumulated detection field from video processing, representing the time-integrated jet distribution and highlighting regions with more than 75% liquid presence.

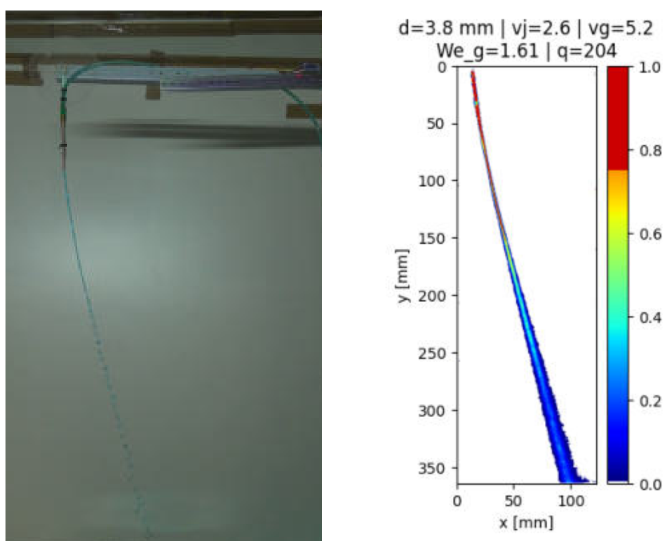

Figure 2. Time-integrated liquid phase detection obtained from OpenCV processing. (Left) Raw camera image. (Right) Accumulated liquid phase detections obtained from OpenCV processing of high-speed experimental recordings.

4. CONCLUDING REMARKS

A Python-based code was developed to process experimental videos and extract quantitative information on liquid jet evolution. For each test, a cumulative detection map is obtained by integrating segmented liquid pixels over all frames, providing a representation of the mean trajectory and dispersion under crossflow. High accumulated values indicate persistent liquid presence, enabling identification of key features such as penetration height, breakup location, and the onset of a fluctuating regime.

The methodology links operating conditions to dimensionless numbers (q and We_g), allowing the construction of penetration curves and empirical fits. These results will be compared with existing correlations to assess deviations. A second test campaign will further expand the parameter space, including jet injection angle and boundary layer effects to better represent agricultural conditions.

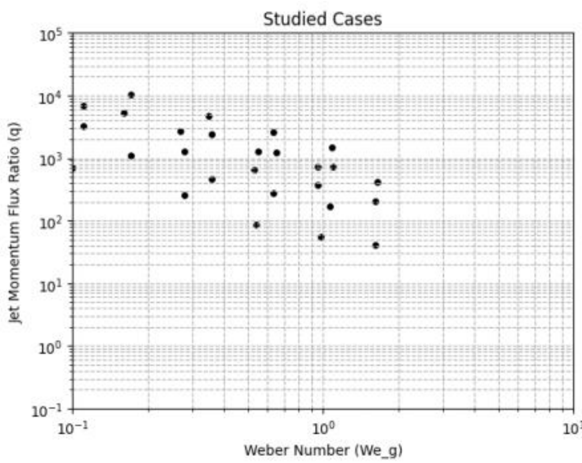

Figure 3. Distribution of studied cases in Weber number (We_g) versus jet momentum flux ratio (q)

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