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Experiments and Large-Eddy-Simulations on particle interaction with a turbulent air jet impacting a wall

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Abstract. Experiments and large eddy simulations are carried out to study the interaction of spherical particles with a turbulent air jet impacting a wall. The context is that of the dynamical air curtains used to separate a contaminated ambiance with passive or inertial particles from a clean ambiance. The jet and particle Reynolds numbers and the Stokes number are respectively equal to $Re_j = 13500$, $3 \leq Re_p \leq 17$ and $0.1 \leq St \leq 1.5$. The rate of particles that crosses the air jet is analyzed according to the particle size, for two particle injection heights. A non-monotonous passing rate of the particles through the jet with respect to the particle size is observed, probably due to the particles/turbulence interaction.

Keywords: plane air jet, air curtain, particle interaction, experiments, LES.

1 Introduction

Plane air jets are widely used in industry and cover a large range of applications: wiping and cooling of a liquid film by a plane turbulent jet [1], spread reduction of fumes and gaseous pollutants in tunnel fires [2] etc. In our case, a plane air jet is used for the separation of two clean and polluted atmospheres by inertial and non-inertial particles. The purpose of this work is to define if large eddy simulations (LES) allow qualitatively and quantitatively reproducing the interaction between particles and a turbulent vertical air jet. In that aim, an experimental apparatus and a numerical tool based on the coupling of LES and a Lagrangian model for the particle transport have been developed. The studied configuration is that of an air jet impacting a wall (similar to that of the experiments [3] and LES [4]) and crossed by particles. The objective is to study the jet dynamics without particle and, then, to inject particles towards the jet, to measure their passage rate through the jet and to compare it with that of the simulations.

2 Analysis of the impinging plane air jet, without particle

2.1 Experimental facility and method

In order to characterize impacting plane air jets, we designed the experimental device of Fig. 1. A vertical plane air jet is generated by a centrifugal fan that blows air through a divergent and convergent channel, then through a rectangular nozzle of section width $e=3$ mm in x-direction and depth $d_z=200$ mm in z direction. The nozzle aspect ratio $d_z/e=66$ ensures that the flow is statistically two-dimensional and free from the effects of the side walls when taking measurements in the central plane ($z = 0$) of the jet. The nozzle outlet is located in the middle of the top wall of a horizontal rectangular channel of height $H=3$ cm, depth $d_z=200$ mm and length $L_x=60$ cm in x-direction (30 cm on each side of the jet). The jet average velocity at nozzle outlet is $\bar{U}_j=65$ m/s. The jet Reynolds number $Re=\bar{U}_j e/\nu=13500$ and the opening ratio $H/e=10$ are fixed in all the study. The analysis of the velocity field is carried out by particle image velocimetry (PIV), by seeding with oil particle tracers directly at the fan level and using a Nd-Yag laser (65mJ, 15Hz) and a fast camera (FS EO 4M-32).

2.2 Flow configuration, LES model and numerical methods

The large eddy simulations are performed with the CFD code Ansys/Fluent v18.2 using the WALE model to deal with the sub-grid effects. The filtered Navier-Stokes equations are solved by a finite volume method with a second order bounded central scheme in space, PISO algorithm and a second order time implicit scheme. The numerical configuration is close to that of the experiments. The computational domain size is $L_x \times L_y(H) \times L_z = 243 \times 30 \times 18.84$ mm³ in the horizontal, vertical and depth directions respectively (Fig 2. left). The vertical plane jet is injected into the domain by a nozzle of section $L_z \times e = 18.84 \times 3$ mm² located in the center of the upper horizontal wall ($H/e=10$). The experimental velocity profile measured in [3] at the outlet of the nozzle and taken up in the LES [4] is interpolated and imposed as inlet boundary conditions (B.C.) in our simulations with the average velocity $\bar{U}_j=65$ m/s. Turbulent fluctuations in the inlet velocity profiles are generated, with a turbulent intensity $I=2\%$, by a « spectral synthesizer ». No slip B.C are imposed on the horizontal walls and periodic B.C. on the front and back faces. The depth $L_z/e=2\pi$ is chosen so that the time signals are decorrelated in z-direction [4]. The air jet impacts the lower wall and horizontally flows out through the left and right vertical openings considered at the atmospheric pressure. A non-uniform Cartesian mesh of size $N_x \times N_y \times N_z = 236 \times 150 \times 64$ cells ($y^+_{\max} < 5.6$) is used (Fig. 2 right). It is uniform in z-direction. The time step is $\Delta t = 10^{-6}$ s such that $CFL_{\max} = (U\Delta t/\Delta x)_{\max} = 7$. The time duration for the statistics is 0.02 s.

2.3 Result presentation and discussion for an air jet without particle

Fig. 3 shows average and rms velocity profiles obtained by the present PIV and LES, compared with experimental [3, 5] and LES [4] results. Other validations were carried out by comparing various vertical and transverse profiles of the time averages and rms of the velocity components and pressure, the Reynolds stresses, the half width of the jet and the spectral analysis of time signals. All these results are in good agreement with the results published in the reference literature.

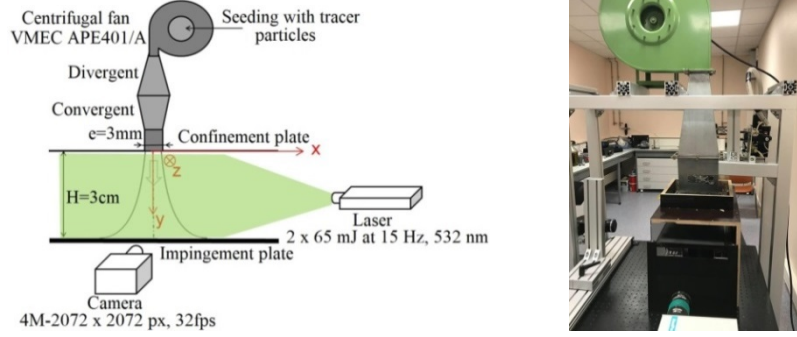


Fig. 1. Sketch and photography of the experimental facility.

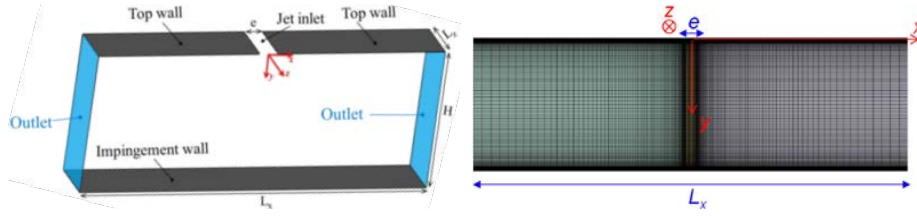


Fig. 2. Sketch of the computational domain (left) and used mesh in the (x-y) plane (right).

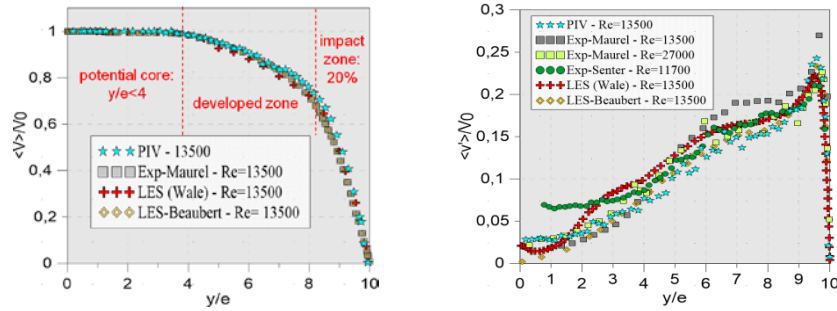


Fig. 3. Mean velocity magnitude (left) and rms of the vertical velocity (right) along the jet axis.

3 Analysis of the jet/particles interaction

3.1 Experimental facility and particle generation (spinning disc)

To generate particles, the spinning disk method is used (Fig. 4 right). The principle is the fragmentation and dispersion of oil droplets under the centrifugal force of a rotating disk. The edge of this disk is placed at 1 cm from the jet axis and its tangential speed is $V_t = R\omega = 50$ m/s with $R = 1.6$ cm. From Fig. 4 and 5, it can be shown that the presence of the rotating disk does not perturb the air jet flow. The oil mass flow rate for particle generation is 0.021 g/s. The local and average particle concentrations and the particle size distribution are measured on the two sides of the jet by an optical particle counter COP-GRIMM (Fig. 4 left). The generated particle size varies between 0.3 and 7 μm .

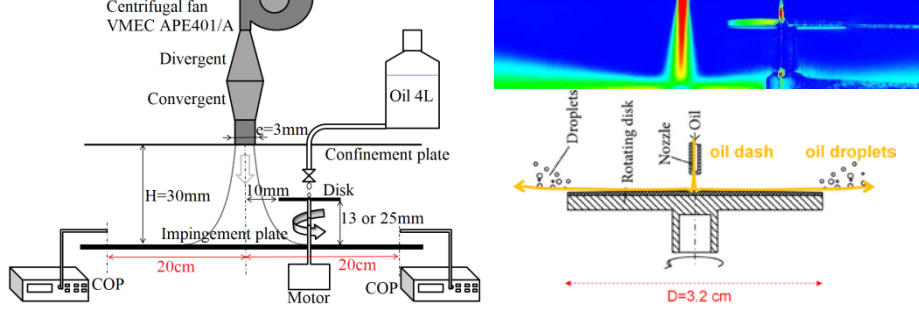


Fig. 4. Experimental facility for the jet/particle interaction study (left). Spinning disk principle (right bottom). PIV contours of the mean velocity magnitude with the rotating disk (right top).

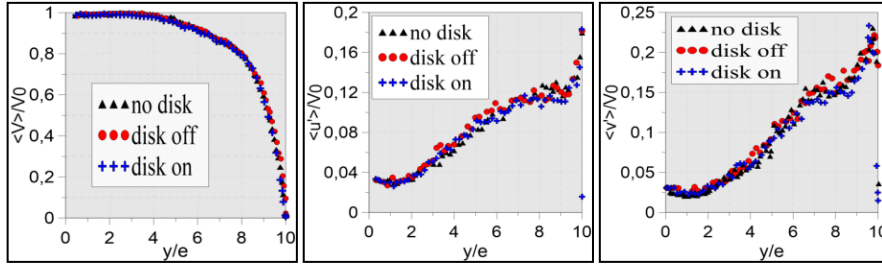


Fig. 5. Profiles of the mean vertical velocity (left) and RMS of the horizontal (middle) and vertical (right) velocities along the jet axis, with the disk or not and with its rotation on and off.

3.2 Configuration and parameters of the jet/particle simulations

A Lagrangian model expressing the balance between the inertial, drag and gravity forces acting on the particles is used for the transport of the oil droplets considered as spheres of diameter d_p and density ρ_p . In this model, the particle relaxation time $t_p = \frac{\rho_p d_p^2}{18\mu} \frac{24}{C_D Re_p}$ and the drag coefficient $C_D = a_1 + \frac{a_2}{Re_p} + \frac{a_3}{Re_p^2}$ ($a_i = \text{cst}$) are function of $Re_p = \frac{\rho_d |\vec{u}_p - \vec{u}|}{\mu}$ the particle Reynolds number. Furthermore a “stochastic tracking model” is activated in Ansys/Fluent to take into account the turbulent dispersion of the particles (see [6] for more details). Since the largest particle volume fraction was estimated around $2 \cdot 10^{-5}$ in the spinning disk neighborhood, a two-way-coupling model was used in the simulations. Furthermore, the Stokes number $St = t_p / t_s$, with $t_s = e / (2u_p)$ the characteristic time of the studied system, is estimated to vary between 0.08 and 1.50 when the oil particle diameter varies between 1 and 5 μm . We can therefore predict that a weak proportion of the particles should go through the air jet under inertial effects. The injection and boundary conditions for the particles are presented on Fig. 6 (left). The spherical particles are injected with a horizontal velocity $u_p = 50 \text{ m/s}$ from a surface of $\text{depth} \times \text{height} = 18.8 \times 1 \text{ mm}^2$, located at 1 cm from the air jet vertical median plane and at -5 mm from the top wall. The particle mass flow rate is 0.005 g/s and the oil density

$\rho_p=920 \text{ kg/m}^3$. The particles are reflected on the top wall and on the bottom wall in front of the air jet nozzle, but they are trapped on the rest of the bottom wall.

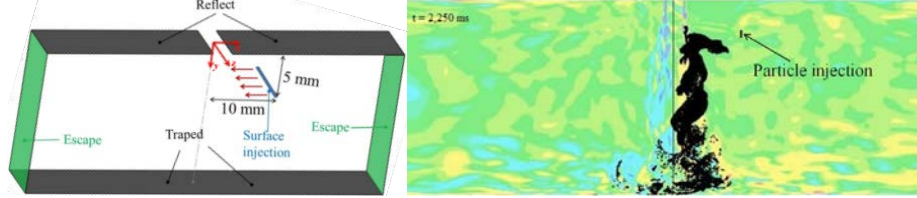


Fig. 6. Simulation domain with the injection line and the particle B.C. (left). Vorticity contours and location of the particles of $4\mu\text{m}$ (black points) in the plane $z=0$ and at $t=2.250 \text{ ms}$ (right).

3.3 Result presentation and discussion for an air jet with particle injection

The time evolution of the total particle concentration, $C_{p,tot}$, measured on the opposite side of the jet with respect to the rotating disk is shown on Fig. 7 (left). There are four distinct phases in this graph: (1) the $C_{p,tot}$ evolution in the environment (before particle injection) in order to subtract it from the following measurements; (2) the $C_{p,tot}$ evolution with particle injection without air jet; (3) the $C_{p,tot}$ evolution with particle injection and air jet (that is the concentration of particles passing through the jet); and (4) the $C_{p,tot}$ evolution after stopping the particle generation. One can see that the repeatability of the experiments is ensured and a decrease in the particle concentration is observed in the presence of the jet. From these measurements, one can deduce the particle passing rate (PPR) through the jet that is the ratio of the average $C_{p,tot}$ values in the presence and absence of the jet. Since, with the used optical counter, the diameter d_p of the particles can be measured, the preceding analysis of $C_{p,tot}$ can similarly be performed to measure the concentration and the PPR for each class of particle size. This is illustrated on Fig. 7 (right) which presents the PPR evolution with respect to d_p . Two positions of the rotating disk are presented: one is located in the jet potential cone at -5 mm from the top wall and the other one in the developed zone at -17 mm (see Fig. 3 left).

In the simulations, the particles are injected at -5 mm from the top wall, only for one class of particle size (d_p is fixed). Fig. 6 (right) shows the particle/vorticity interaction for $d_p=4 \mu\text{m}$. The particles are driven by Kelvin Helmholtz rolls that are partially responsible for the passage of the particles through the jet, mainly in the impact zone. Fig. 7 (right) compares the experimental and numerical results. For the injection at -5 mm , the experimental and numerical PPR are in a relatively good agreement: the maximum absolute discrepancy is 10%. A non-monotonous PPR evolution with d_p is clearly visible in the experiments but is not reproduced by LES. In the experiments, the larger value of the PPR for the smallest d_p could be due to the turbulent dispersion of the smallest particles while its increase for the largest d_p could be due to inertial effects. The PPR evolution for an injection at -17 mm is similar to that at -5 mm but with larger values due to the horizontal transport of the particles by the larger turbulent Kelvin-Helmholtz rolls (see Fig. 6 right).

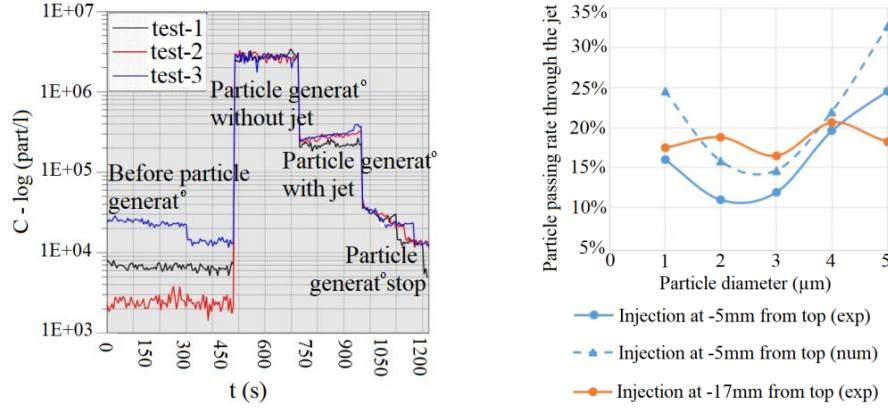


Fig. 7. Time evolution of the particle concentration (left). Evolution of the passing rate of the particles through the jet with respect to the particle diameter (right).

4 Conclusion

In the first part of this study, an analysis of the air jet dynamics without particles has been performed with PIV and LES simulations. The comparison of the results has shown that the Wale LES model is appropriate to simulate a turbulent air jet impacting a wall. In the second part, the interactions between this air jet and spherical particles of different diameters was investigated by the two approaches. The method of particle generation by a spinning disk has appeared to be a very interesting method because it does not perturb the jet. The experiments allowed us to set up reference results to validate the simulations with particle/jet interaction because no reference experiment exists in the literature for this configuration. The LES detailed results allow us a better understanding of the particle/jet interactions, in particular the interactions with the Kelvin-Helmholtz rolls. This paper is a presentation of the first results of this study but new results and deeper analyses are in progress.

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