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Experimental Investigation on the Pollutant Dispersion Driven by a Condensed-Phase Explosion in an Urban Environment

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The atmospheric dispersion in an urban or industrial environment is well documented in the literature. However, there is a lack of knowledge about the dispersion triggered by rapid and short phenomena such as explosions. The presented research provides information about the pollutant dispersion caused by a condensed-phase detonation in an urban environment. Experimental campaigns are conducted inside a subsonic wind tunnel at a 1:200 reduced scale. An explosion leading to the dispersion of solid particles is experimentally simulated in free field and in a straight street under a controlled neutral urban atmospheric boundary layer. Exploding-bridge-wire detonators are used to disperse a micro-talc powder. The pollutant dispersion and the overpressure caused by the explosion are measured respectively through a fast response optical measurement technique and fast response pressure sensors. The effects of key parameters on the dispersion are investigated. Two gram-scale detonators are used to analyze the effects of the explosion energy. The effect of the powder is studied through two masses of a micro-talc powder. Additionally, the transition between the predominance of the effect of the explosion and the predominance of the effect of the wind is analyzed with three wind velocities. The velocity field of the dispersion is obtained for each time step through Large Scale Particle Image Velocimetry. Similarly, the dispersion is investigated inside a T-junction to highlight the effect of an urban configuration on the pollutant release. This project provides a strong experimental database about dispersion driven by an explosion. A better understanding of the phenomenon can be used to improve industrial safety and security through more reliable predictions.

1. Introduction

Examples of tragedies caused by explosively driven dispersion are numerous. Some of them include the dispersion of dangerous chemicals in the atmosphere such as the explosion of a warehouse in Tianjin, China in 2015 (Aria, 2017). Some others are linked to dust dispersion serving as fuel to secondary dust explosions such as the accident in Imperial Sugar manufacturing facility in Georgia, US in 2008 (US CSB, 2009). Although the atmospheric dispersion is widely studied in the literature, only a few studies focus on the dispersion driven by an explosion, resulting in a short duration dynamic source at high velocity. Yet it is an essential knowledge for the development and the validation of efficient tools for predicting the dispersion of a cloud following an explosion, in open field as well as in urban areas. To ensure an accurate and reliable prediction of the plume dispersion after an explosion, it is necessary to base the modeling on reliable empirical data. Investigations can be found in the literature. The rapid dispersion of inert spherical steel particles (Zhang et al. 2001, Frost et al., 2007), glass bubbles (Sturtzer, 2014) or liquid (Li et al. 2010) after a detonation has been investigated using a high-speed camera. The dispersion turned out to depend on the pollutant characteristics (solid or liquid) and the geometry of the explosive charge. However, the existing studies focus on the near-field effects of the explosion, few milliseconds after the detonation. An effort has still to be made to improve the experimental database on the dispersion of the puff inside an atmospheric boundary layer (high-speed to low-speed interface). The objective of this research is the study of the pollutant dispersion caused by an explosive charge. To achieve it, the dispersion is experimentally simulated on a reduced scale of 1:200 in a

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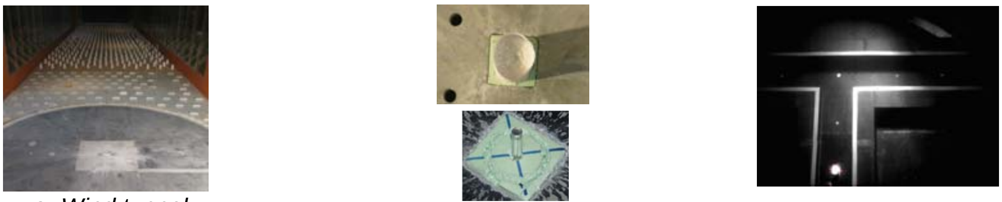
subsonic wind tunnel that reproduces an atmospheric layer typical of an urban environment. The velocity fields of the dispersion are obtained via Large Scale Particle Image Velocimetry (LS-PIV). Numerous investigations have demonstrated the applicability of LS-PIV method in the study of flows such as the work of Gopalaswami et al. (2016) on liquefied natural gas boiling when it comes into contact with water or the work of Jenkins et al. (2013) on the velocity field of metallic particles after a detonation. The effects of various parameters on the dispersion by explosives in free-field are presented in this paper. Three wind velocities (no wind, 3 m/s and 5 m/s), two masses of pollutant, and two energies of detonation are taken into consideration. Similarly, the dispersion is investigated inside a T-junction and compared to a dispersion in free-field to highlight the effect of an urban configuration on the cloud.

2. Material and Methods

The experimental set-up has been designed to conduct non-destructive studies of air-blast in free field and in urban configurations under a controlled atmospheric boundary layer. Experiments are performed inside a subsonic wind tunnel 2 meters high, 3 meters wide and 20 meters long with a roughened floor to allow the growth of a turbulent boundary layer similar in nature to the lower part of a neutral atmospheric layer in a 1:200 reduced scale. The flow is illuminated with a strong light source set on the side of the wind tunnel. A Phantom V7.1 high-speed camera is used to visualize the dispersion and acquires at a frequency of 10869 Hz. The camera can be set on the side of the wind tunnel, under the light source, to provide a side view of the dispersion or on the wind tunnel roof, to provide a top view. The effect of the explosive source is investigated through two kinds of exploding-bridge-wire detonators: RP80 and RP83, distributed by RISI. The TNT equivalents of the two explosives have been experimentally estimated at 0.136 g and 1.31 g respectively for the RP80 and the RP83. More details about the detonators used can be found in Fouchier et al. (2017). The dispersion is simulated using a talc powder, distributed by Imerys, with an average particle size of 7.8 μm and a loose bulk density of 0.44 g/cm^3. The powder is maintained around the explosive by a paper cylinder. As the powder affects the energy of the explosion, involving a blast damping, the homogeneity of the powder distribution is systematically checked using pressure sensors set around the explosive. The dispersion is studied in free-field and inside a T-configuration. The urban configuration, built with 1 cm thick wood boxes which are 15 cm large, 20 cm long and 10 cm high, represents a typical street junction in a 1:200 reduced scale. The street is 25 cm wide and the explosion occurs before the junction. A top view of the dispersion is used to visualize the plume inside the street. Pictures of the experimental setup are given in Figure 1.



a- Wind tunnel

b- Pollutant source (up) and explosive (down)

c- T configuration (top view)

Figure 1: Experimental setup

The dispersion of the solid particles is investigated through the variation of the area and the velocity field of the plume. The area of the cloud is accessed from the contour of the plume obtained via image post-processing. The velocity field is obtained by LS-PIV. A preliminary parametric study has led to the selection of a 64 pixels interrogation window, refined in 3 steps to 8 pixels, an overlap of 50% and a separation time between two images of 0.5 ms up to 46 ms after the explosion and 1 ms after this time (Fouchier et al, 2018).

3. Results and Discussion

3.1 Dispersion in free field

The dispersion is accessed via the LS-PIV technique. Examples of the velocity maps obtained for the dispersion of 28 g of talc powder driven by the explosion of a RP80 under a calm atmosphere are given in Figure 2. Before 20 ms, the dispersion is underestimated by the technique due to the 3D geometry and a transversal view with a laser sheet is needed to obtain the proper velocity magnitude. However, the analysis presented here gives satisfactory results concerning the direction of the vectors.

Before 2.7 ms, the cloud is too small and compact to be studied by LS-PIV and the velocity of the plume expansion is obtained via a contour analysis. The contour expansion velocity is proposed in Figure 3. Two dispersion patterns are observed: one spreading horizontally at the ground level and one dispersing vertically in the air. This geometry is due to the distribution of the powder and the blast propagation which are both cylindrical. The particles around the detonator will affect the horizontal dispersion while the particles over the detonator will affect the vertical dispersion. In the first milliseconds after the explosion, the horizontal dispersion is predominant, as it can be seen in the contour expansion analysis. After a couple of milliseconds, the vertical component of the dispersion prevails.

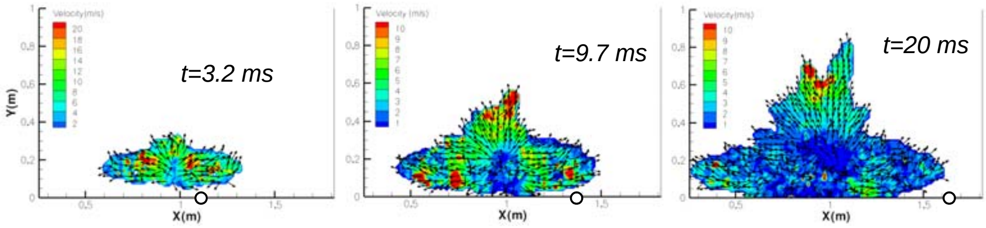


Figure 2: Velocity cartographies of the dispersion of 28 g of talc powder driven by a RP80 in free field

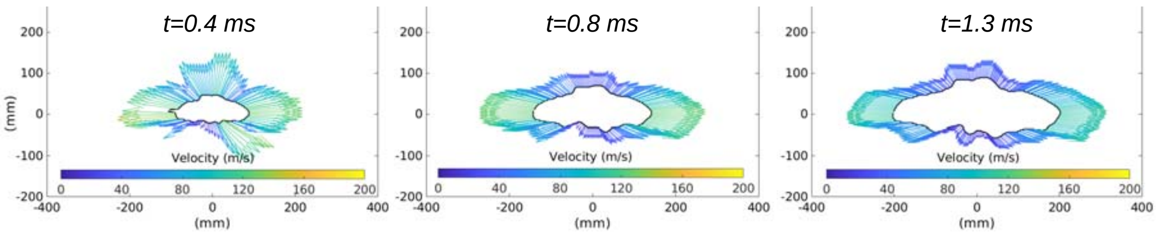
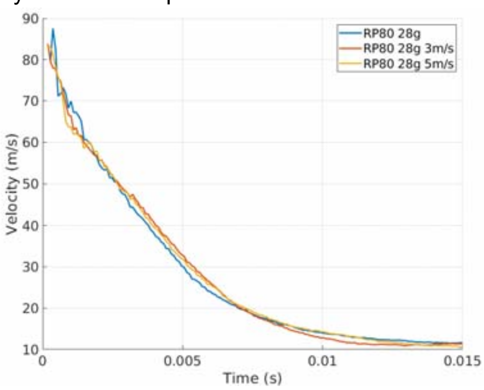
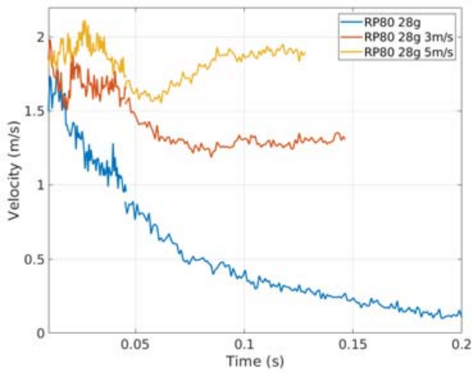


Figure 3: Expansion velocity of the contour of the plume in free field under a calm atmosphere (RP80, 28 g)

The averaged velocity of the dispersion is obtained with the combination of the two analyses. Figure 4 gives the averaged velocity of a dispersion of 28 g of talc powder driven by a RP80 under a calm atmosphere and under a wind of 3 m/s and 5 m/s. Before 15 ms, the velocity is obtained via the contour (Figure 4a) and after, the velocity is obtained via LS-PIV (Figure 4b). The averaged velocity is obtained by averaging the magnitude of the velocity vectors. Before 15 ms, the wind does not affect the dispersion, the effect of the explosion is predominant and expansion velocities up to 90 m/s can be observed. The velocity decreases exponentially with time until reaching the velocity of the atmospheric wind. The velocity profiles at 20 ms, 100 ms, and 160 ms after the explosion, obtained via LS-PIV, are proposed in Figure 5. The averaged horizontal component of the velocity is represented by solid lines while the vertical component is given by dashed lines. The averaged vertical dispersion is similar for the three wind velocities, highlighting the fact that the wind does not have a major effect on the vertical dispersion. Contrarily, the horizontal velocity increases with the height similarly to the wind velocity profile of the atmospheric boundary layer applied. Under a calm atmosphere, the symmetrical dispersion leads to a null horizontal averaged velocity.



a) Averaged velocity of the cloud expansion 0-15 ms



b) Averaged velocity of the dispersion (LSPIV) 15 ms -200ms

Figure 4: Averaged velocity of the dispersion of talc powder under three atmospheric conditions (RP80, 28g)

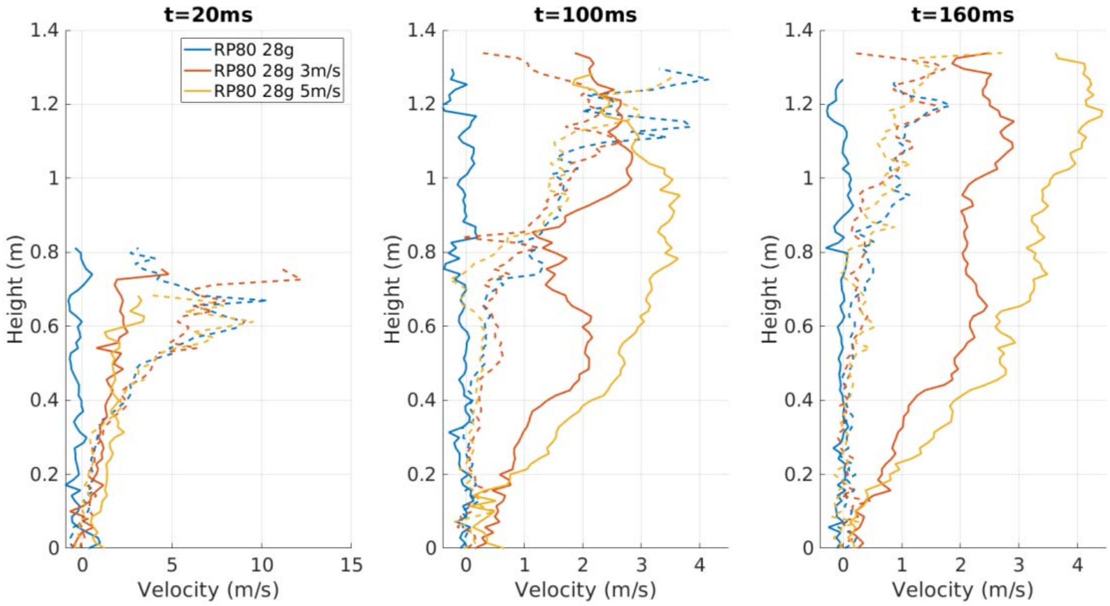
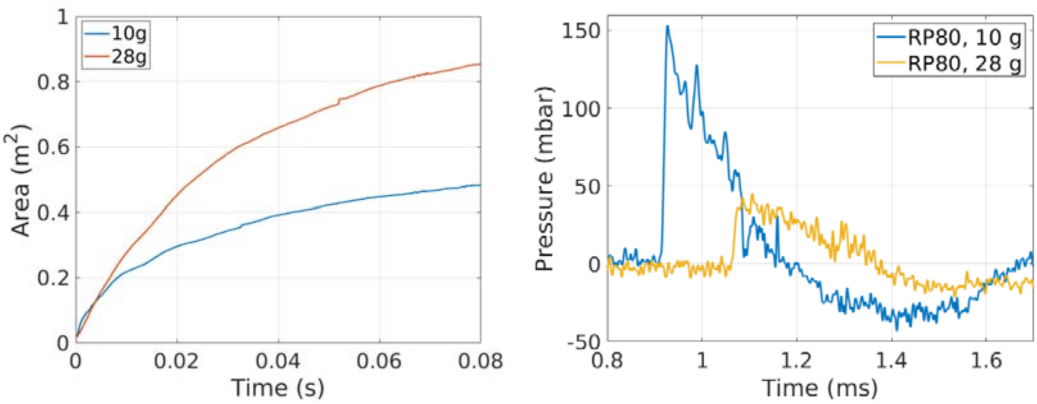


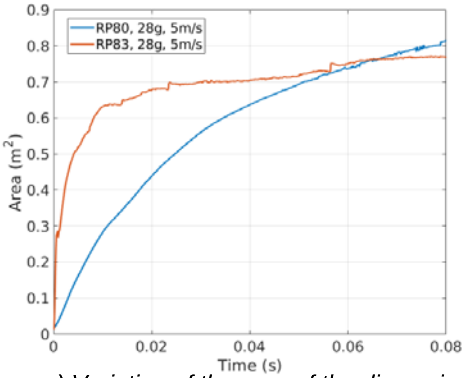
Figure 5: Velocity profiles of the dispersion of 28 g of talc driven by a RP80 under three atmospheric conditions (dashed line: vertical component of the velocity, solid line: horizontal component of the velocity)

The effect of the mass of the powder is studied by comparing the dispersion of 10 g and 28 g of talc powder under a calm atmosphere. A smaller paper cylinder is used for the 10 g test to ensure the same distribution of the powder around the detonator. The variation of the cloud area from the explosion of a RP80 is proposed in Figure 6a. As it can be observed from Figure 6b, giving the blast waves registered at 350 mm from the explosion for the two different talc masses, the energy of the detonation decreases as the mass of powder increases. This effect can be observed at the first moments of the dispersion, where the area of the cloud containing the lowest mass of particles presents the fastest increase. After 4 ms, an inversion occurs and the cloud containing the highest mass of powder presents the largest area. The effect of the energy of the explosion on the dispersion is investigated using a RP80 and a RP83 under a wind of 5 m/s. The variation of the cloud area is given in Figure 7a. For an identical mass of powder, the expansion of the plume is faster when the detonation is stronger. However, the clouds reach a similar area once the effect of the explosion is dissipated. The shape of the plume is also affected by the type of detonator used, as shown in Figure 7b where the pictures of the dispersion 92 ms after the explosion for the two detonators are proposed. As the RP83 is taller, the quantity of powder above the detonator is lower, leading to a lower dispersion in altitude.

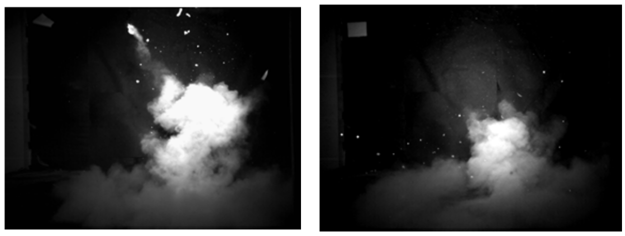


a) Variation of the area of the dispersion *b) Blast wave at 350 mm from the explosion*

Figure 6: a- Variation of the area of the dispersion of two masses of talc powder driven by a RP80 under a calm atmosphere; b- Blast wave registered at 350mm from the explosion of a RP80 surrounded by two masses of talc powder



a) Variation of the area of the dispersion



RP80 *RP83*

b) Pictures of the dispersion (92 ms)

Figure 7: a- Variation of the area of the dispersion driven by a RP80 and a RP83 under a wind of 5m/s, b- Pictures of the dispersion 92 ms after the explosion of a RP80 (left) and a RP83 (right)

3.2 Dispersion inside a T-configuration

The dispersion is investigated inside a T-junction under a calm atmosphere to analyze the effect of an urban configuration on the dispersion. The velocity maps at three different moments of the dispersion are proposed in Figure 8 while the contour expansion velocity in the first milliseconds is given in Figure 9. The buildings are represented by white or grey rectangles. At 0.7 ms, the plume reaches the walls. Before this moment, the effect of the confinement is visible with a decrease of dispersion speed in the buildings direction. As it can be observed from the velocity maps, the plume is contained inside the street in the first milliseconds of the dispersion. After 10 ms, the plume starts to disperse over the configuration. The results can be compared to a free field dispersion, which analysis results are given in Figure 2 and Figure 3. It appears that the effect of the confinement increases the velocity of dispersion inside the street.

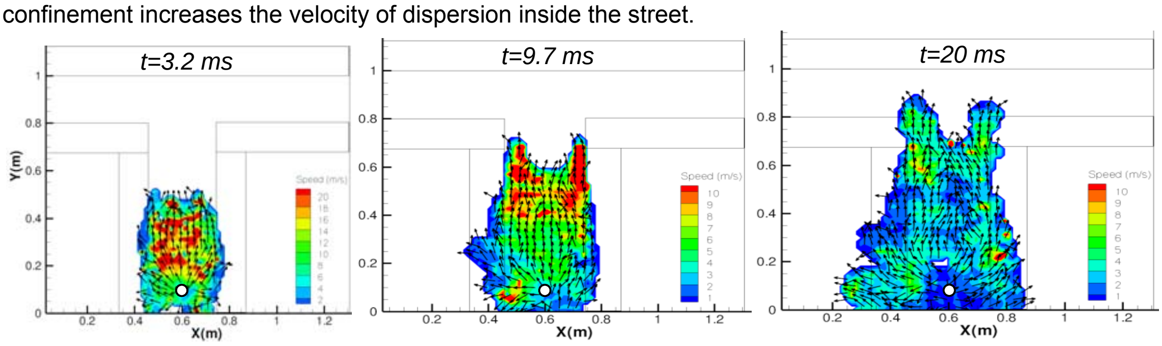


Figure 8: Velocity maps of the dispersion of 28 g of talc powder driven by a RP80 inside a T configuration (top view) - position of the detonator given by a white circle, positions of the buildings are given by white rectangles.

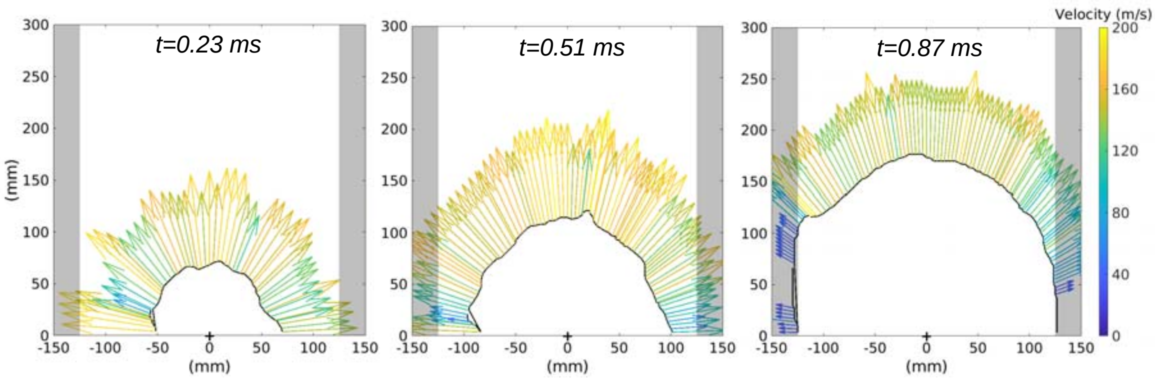


Figure 9: Expansion velocity of the contour of the plume of 28 g of talc powder driven by a RP80 inside a T-configuration under a calm atmosphere (explosive position indicated by a cross)

4. Conclusions

The dispersion driven by an explosion is investigated in free field and inside a T-junction in a subsonic wind tunnel at a 1:200 reduced scale. To obtain the velocity of dispersion, the contour expansion is accessed at the first milliseconds of the dispersion, then the Large Scale Particle Image Velocimetry (LS-PIV) is applied to obtain the map of the velocity inside the plume. Several conclusions can be drawn from the effect of the different parameters tested on the dispersion. In the first milliseconds, the dispersion is mainly horizontal while after 10 ms, the vertical dispersion predominates. Before 10 ms, the effect of the explosion is predominant, and the atmospheric condition does not affect the dispersion. The effect of the wind is visible after this moment on the horizontal dispersion whereas the vertical dispersion is relatively unaffected by the flow. The mass of the powder has an important effect on the dispersion. The dispersion just after the explosion will be faster for a lower mass of powder. After 4ms, an inversion occurs, and the dispersion is larger for a higher mass of powder. The distribution of the powder is also important: the particles around the detonator affect the horizontal dispersion while the particles over the detonator affect the vertical dispersion. Finally, the dispersion is investigated inside a T-junction. The street configuration confines the dispersion, resulting in higher velocities of dispersion compared to the free field.

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