THE BEHAVIOR OF WINDBORNE DEBRIS ACCOMPANYED BY A TRAVELING TORNADO

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ABSTRACT

We demonstrate the flying and deposition of windborne debris by a traveling tornado. The traveling tornado was generated with our original tornado simulator. Its velocity field near surface was measured by a dynamic PIV. Polystyrene particles of 0.8 mm in diameter were employed as windborne debris. The horizontal velocity field of the tornado showed an asymmetric pattern in which the large velocity region was observed in the right and rear side of the moving direction. The polystyrene particles in the right hand side of the tornado trajectory were also blew out broadly. Such windborne debris deposited like spiral pattern corresponding to the spiral flow converging to the tornado axis.

KEYWORDS: TORNADO, WINDBORNE DEBRIS, DYNAMIC PIV

Introduction

Windborne debris is the most dangerous matter in wind disaster. The behavior of windborne debris by gusty wind is studied by [Tachikawa (1983, 1988)], [Holmes (2004)] [Lin et al.1006]] and so on. But, the behavior of debris accompanied by a tornado has never been studied well. This is because the velocity fields of actual traveling tornadoes are not measured in detail. Moreover, they are not also obtained experimentally because experimental simulations of traveling tornadoes are very rare except of [Haan et al. (2008)].

The objective of our experimental study is to investigate the behavior of the debris by a traveling tornado. We generated a traveling tornado using our original tornado simulator [Sassa et al. (2007)] and measured the velocity field near surface by using a dynamic PIV. The trajectories of small sphere particles were also obtained with the data of the PIV and they were compared to the behavior of the debris filmed by a hi-speed camera.

Experiment

Our tornado simulator is composed of an axial fan to generate updraft and a rotating porous disk to give angular momentum to the flow field, as shown in Fig. 1. The simulator does not have any closed test chamber. Then we can easily move a tornado-like vortex by traversing it. In order to generate strong and stable tornadoes, the updraft velocity, \( U_L \), and the rotation rate of the porous disk, \( \Omega \), were set to 270 mm/s and 33.5 rad/s, respectively. The moving velocities of the simulator were set to \( U_c = 20 \) and 80 mm/s. The horizontal plane at \( z = 4 \) mm was illuminated by an Argon laser sheet and filmed by a hi-speed camera at 1000 fps in flame rate. The velocity fields were calculated from the resultant movies through a dynamic
PIV method. The baby powder of 5 μm in diameter was employed as the tracer of the PIV. Polystyrene sphere particles of 0.8 mm in diameter and of $4.1 \times 10^{-6}$ g in weight were used as windborne debris and were spread uniformly over the ground. The behavior of them was also filmed through the hi-speed camera at 500 fps and a handy-cam.

**Calculation of trajectories**

The motions of polystyrene particles in horizontal wind of a simulated tornado-like vortex were calculated numerically similar to [Holmes(2004)]. The particles were assumed to move due to drag only without lift and side force. At this time, we can get just horizontal velocity components in horizontal planes and cannot evaluate the updraft of the tornado-like vortex. Therefore, horizontal motions of the particles were calculated in the present study.

Two velocity components, $u_{mx}$ and $u_{my}$, of the particles are given by following equations of motion.

$$\frac{du_{mx}}{dt} = \frac{\rho_a C_D}{2 \rho_m \ell} (U_x - u_{mx})^2, \quad \frac{du_{my}}{dt} = \frac{\rho_a C_D}{2 \rho_m \ell} (U_y - u_{my})^2,$$

(1)

where $U_x$ and $U_y$ are the horizontal velocity components of the tornado-like vortex, $\rho_a$ and $\rho_m$ are the densities of air and particles, $C_D$ is the drag coefficient, and $\ell$ is the characteristic length. The coefficient of Eq. (1) is 0.2375 in the present equation. After the short time, $\Delta t$, the particle moves to $(x_m, y_m)$, accelerating uniformly up to the velocity, $(u_{mx}, u_{my})$, by the wind velocity, $(U_x, U_y)$, at the initial location, $(x_{m0}, y_{m0})$, as follows,

$$x_m = x_{m0} + u_{mx}\Delta t + \frac{1}{2} \frac{du_{mx}}{dt} \Delta t^2, \quad y_m = y_{m0} + u_{my}\Delta t + \frac{1}{2} \frac{du_{my}}{dt} \Delta t^2$$

(2)

We numerically calculated the trajectories of particles with the velocity fields obtained through the PIV method. For the traveling tornado, the velocity field was moved toward positive $x$-direction at the uniform traveling velocity of the tornado-like vortex, $u_c$, which is slightly smaller than the moving velocity of the simulator.

**Results and Discussion**

**Stationary tornado**

The mean velocity distributions of a tornado-like vortex at $z = 4$ mm and $z = 14$ mm are shown in Figures. 2(a),(b). The counter-clockwise rotating motion is clearly observed at both heights. The converging flow toward the center axis is also observed at $z = 4$ mm but there is only rotating motion at $z = 14$ mm. The boundary layer thickness was 14 mm in the
present tornado-like vortex [Sassa et al. (2007)]. The calculated trajectories of particles initially set at several points are also shown in Figure 2. The particles concentrate around the vortex axis due to the converging flow at $z = 4$ mm as shown in Figure 2(a). Therefore, most of particles accumulate around the center axis drawing spiral pattern as shown in Figure 3. But, some particles fly out of rotating motion shown by the trajectory of tracers as shown in Figure 4 in spite of the converging flow existing in the boundary layer. Such motion resembles the trajectories of the particles at $z = 14$ mm where the converging flow does not exist as shown in Figure 2(b). The different between the calculation and the experiment is
caused by the updraft of the tornado. If we can measure the 3-dimensional velocity field of the tornado, the prediction of windborne debris will be more accurate.

**Traveling tornado**

Figure 5 shows mean velocity fields of a traveling tornado-like vortex. They show asymmetric patterns in which the large velocity region locates in the right and rear side toward the moving direction. Such pattern is caused by the existence of converging flow toward the vortex axis additional to rotating flow in the boundary layer. Therefore, Rankine vortex in which the large velocity region of a traveling tornado locates in the right side of the moving direction is not a good approximation of the tornado near surface. The intensity of the large-velocity region seems to be larger with the moving velocity, $U_c$. This fact may be

![Image of velocity distribution](image)

**Figure 5:** The velocity distribution of the moving vortex at $Z=4\text{mm}$

![Image of traveling tornadoes](image)

**Figure 6:** Traveling tornado-like vortices inclined forward visualized with dry ice mist
caused by both of the addition of the traveling speed and the effect of ‘vortex stretching’ due to the inclination of the vortex as shown in Figure 6.

The particles are blown away by the passage of the tornado-like vortex as shown in black area in Figure 7. Therefore, the black area corresponds to the area damaged by the tornado. Its width is larger in the right hand side of the trajectory of the vortex axis. On the other hand, the deposition of particles is observed near the trajectory of the vortex axis. Such asymmetric distribution, of course, is due to the asymmetric velocity distribution of the vortex, and is quite similar to the distribution of the damaged area caused by an actual tornado as shown by [Wurman and Alexsander (2005)]. The damaged area and the band of deposition become narrower as moving velocity faster. The deposition draws spiral pattern at \( U_c = 20 \text{ mm/s} \) as shown in Figure 7(a), which shows that the converging flow is dominant in this case.

The trajectories of particles in a traveling tornado-like vortex calculated from the data
in Figure 5(a) draw oval patterns slanting downstream as shown in Figure 8. The moving velocity of the tornado-like vortex is slightly smaller than $U_c = 20$ mm/s due to the friction of the floor. The oval pattern results in the spiral deposition of particles as shown in Figure 7(a).

Figure 9 demonstrates the temporal changes of wind velocity at fixed observation points corresponding to the passage of the tornado. Where, the tornado axis is shown by $y = 0$ mm and the positive value of $y$ denotes the left hand side of the axis. These vectors were reanalyzed from the mean velocity field shown in Figure 5(a). The wind direction drastically changes between before and after the passage of the tornado-like vortex at $t = 0$ s. The maximum velocity is observed at the right hand side of the tornado-like vortex at $t = 0.6$ s, after the passage of it.

![Figure 9: The temporal change of wind velocity at fixed observatories](image)

![Figure 10: The flying and deposition of debris through the passage of the tornado-like vortex](image)
The motions of debris at the periods as shown by vertical lines (a) to (d) in Figure 9 are illustrated in Figure 10. The tornado-like vortex moves from back to front of these figures. At the first, the debris is rolled up by the leftward wind of the tornado-like vortex as shown in Figure 10(a). And then, the debris rotates around the vortex axis as shown in Figures 10(b),(c). After the tornado-like vortex passed through the bank of particles, the only left hand side of the particle bank pointed by an arrow in Figure 10(d) was damaged and gullied up. Such temporal change clearly demonstrates the aspect that the structure is destroyed and the windborne debris is caused by the tornado. We expect to obtain detailed quantitative data by making a dynamic PIV in near future. The spiral pattern observed on the ground surface results from the accumulation of the particles drawing oval trajectories as shown in Figure 8.

Conclusions

The horizontal movement of windborne debris was evaluated from the mean velocity field of the tornado-like vortex except for the effect of the gravity force and updraft of the tornado. It clearly demonstrated the accumulation of particles around the vortex axis in the lower layer and the fly outward of the vortex in the upper layer.

The velocity field near surface of the tornado-like vortex has an asymmetric pattern in which the large velocity region located in the right and rear side toward the moving direction. The width of debris blown away was larger in the right hand side of the trajectory of the tornado-like vortex. The process of structure breakdown was also demonstrated through the passage of the tornado-like vortex. The spiral pattern of deposition was made from the debris gathered in the low-speed flow converging to the vortex axis.

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References


