Influence of incident flow conditions on generation of tornado-like flow

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\section*{ABSTRACT}

When evaluating occurrences of strong wind disasters, it is necessary to clarify the characteristics of tornado wind fields near the ground, such as whether or not there are differences from usual atmospheric boundary layer flow. A tornado simulator of the same type as Word (1971) has been developed to examine the characteristics of tornado flow fields. Visualization experiments have been conducted for various inflow conditions of the confluence layer and shapes of tornado-like flows have been observed. Two cases have been studied regarding supply circulation to the confluence layer, using guide vanes and applying shear flows. Wind speed measurement experiments have been conducted for different floor roughnesses and their effects have been studied.

\section*{INTRODUCTION}

Damage due to local meteorological disturbances such as tornadoes, downbursts etc., has been reported in Japan in recent years (Tamura 2007a, 2007b, Miyagi 2007). Those disturbances cause severe winds, but their occurrence is so local that it has not been possible to obtain enough information about them. Therefore, wind resistant design has not allowed for their effects.

Laboratory experiments have been conducted to obtain basic information on tornado-like flow, and some basic characteristics have been investigated.

\section*{OUTLINE OF EXPERIMENTAL SETUP}

\textit{Tornado Simulator Setup}

Because frequent full-scale observations were hard to conduct, in-lab experiments have been carried out for researchers. Ward (1972) developed an original tornado simulator for the lower part of an atmospheric boundary layer under mesocyclone wall clouds where kinematic momentum is predominant. A similar type of facility was used in the present studies.

An outline of the experimental setup is shown in Fig-1 and Fig-2. The simulator had a top fan that generated an updraft at an updraft hole. Through the updraft hole and the confluence region, surrounding air flows into the convection region. To generate swirl flow in the confluence region, air should be circulated around the periphery. In this experiment the circulation was achieved by setting guide vanes as shown in Fig-2.
MODEL OF TORNADOES

In tornado-like flow, height of confluence region, radius of updraft hole, inflow angle and speed to the confluence region are typical dimensional variables, which were estimated by Church (1979) as shown in Table-1. Using these dimensional variables, dimensionless variables can be constructed. They are aspect ratio between updraft radius and confluence height, Reynolds number and swirl ratio.

In some researches, the Reynolds number is defined as,

\[ \text{Re} = \frac{Q}{\nu}, \tag{1} \]

where \( Q \) is flow rate to unit height of the confluence layer, \( \nu \) is kinetic the viscosity coefficient.
The Reynolds number in this study is much smaller than that at full scale, but it was evaluated such that it did not greatly affect the formation of the tornado-like flow (Mitsuta, 1984).

The swirl ratio represents the swirl flow condition, defined as,

\[ S = \frac{R}{2h} \tan \theta . \]  

(2)

where \( R \) is the radius of the updraft hole, \( h \) is the height of the confluence region and \( \theta \) is the inflow angle depending on the vane angle.

The tornado-like flow depended greatly on the swirl ratio (Mitsuta, 1984). The value in this study was in the range of full scale values.

**Measurement Setup**

Through a visualization experiment, variations of flow shapes were studied under different experimental conditions. Wind velocities were measured for some typical flow shapes.

In the visualization experiment, water mist was supplied from the bottom of the confluence region. To enhance their shapes, the mist was illuminated by a laser light sheet. The following two cases were tested to evaluate the effects of flow conditions in the confluence region.

- (1) Setting the vane angle to control the incident flow
- (2) Blowing unsymmetrical flows that have horizontal shear without vanes

In the velocity measurement experiments, laser-Doppler velocimetry (LDV) was used for several swirl ratios using guide vanes. The tangential component was measured assuming that the center of rotational flow was identical to the experimental facility's center. The effect of floor roughness was evaluated in these cases.

<p>| Table 1: Comparison between parameters of full-scale and modeled vortices |
|---------------------------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>full-scale*</th>
<th>present model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>quantity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>updraft radius ( R )</td>
<td>1 – 3 km</td>
<td>0.15 m</td>
</tr>
<tr>
<td>convergence height ( h )</td>
<td>0.5 – 2 km</td>
<td>0.2 m</td>
</tr>
<tr>
<td>flow rate ( Qh )</td>
<td>( 10^8 ) – ( 10^9 ) m(^3)/s</td>
<td>0.3 m(^3)/s</td>
</tr>
<tr>
<td>circulation ( \Gamma )</td>
<td>( 2.5 \times 10^4 ) – ( 2.5 \times 10^7 ) m(^2)/s</td>
<td>0.25 – 3.8 m(^2)/s</td>
</tr>
<tr>
<td><strong>dimensionless number</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aspect ratio ( h/R )</td>
<td>0.2 ~ 1</td>
<td>1.3</td>
</tr>
<tr>
<td>swirl ratio ( S )</td>
<td>0.05 ~ 2</td>
<td>0.07 ~ 1.0</td>
</tr>
<tr>
<td>Reynolds number ( Re )</td>
<td>( 10^9 ) ~ ( 10^{11} )</td>
<td>( 9.4 \times 10^4 )</td>
</tr>
</tbody>
</table>

*) Church 1979
RESULTS OF VISUALIZATION

SHAPE OF SWIRL FLOW AND ITS SWIRL RATIO

Figures 3(a) to (g) show the variation of flow shapes for various vane angles. At swirl ratio $S=0.07$ (corresponding to vane angle 10 degrees) no clear swirl flow was observed near the floor. A small core was formed at the top of the confluence region near the updraft hole. From $S=0.14$ (20 degrees) to $S=0.31$ (40 degrees), tornado-like flows were formed from the bottom of the confluence region at the floor, and they showed laminar flows. At $S=0.45$ (50 degrees), swirl flow started to break from the upper part. This spread to all of the swirl flows at $S=0.65$ (60 degrees). At $S=1.0$ (70 degrees), the vortex core was turbulent and extended in size.

The relation between swirl ratio and vortex shape is shown in Fig-4, and compared to the results by Church (1979) and Monji (1985). As Church showed results for variation of Reynolds number, the results for the same Reynolds number as this experiment, $Re=10^5$, are illustrated in Fig-4. Monji's experiments were for a slightly smaller Reynolds number, and are indicated as a reference. Turbulent flow occurred at swirl ratios higher than $S=0.3$. This result for transition swirl ratio agrees with Church's result, while Monji's result shows a lower transition swirl ratio $S=0.2$.

Multi-cell vortices occurred for $S>0.6$ in Church's result and for $S>0.5$ in Monji's result, while in the present study no multi-cell was observed. Only an expanding core was observed in this study.

SHAPE OF SWIRL FLOW WITH HORIZONTAL SHEAR FLOW IN CONFLUENCE REGION

For a full scale tornado and an atmospheric boundary layer, there are no guide vanes to produce circulation. The circulation was thought to be caused by geometrical effect or non-uniformity of flow along the cold front that causes horizontal shear. In this and following sections, the guide vanes were removed from the simulator and horizontal shear flow was applied to the confluence region from outside. In this section, uniform flow was applied to half of the region, which could cause horizontal shear near the center of the confluence area. Swirl flows were observed for various updraft speeds, from 1 to 6 m/s, at a constant horizontal shear flow speed of 1.4 m/s.

Visualized images are shown in Figs-5 (a) to (e). For lower updraft speeds such as 1 to 2m/s, no tornado-like flow was observed, while for 4 to 6 m/s updraft speeds, tornado-like flows were clearly formed.

SHAPE OF SWIRL FLOW WITH HORIZONTAL FLOW OVER NON-UNIFORM ROUGHNESS IN CONFLUENCE REGION

In this part of the experiment, roughness blocks were distributed non-uniformly over a 1.8 m fetch length and continuously over the floor of the confluence region, and incident flow was applied to the confluence region. The roughness blocks were placed non-uniformly over half of the floor. They comprised cubes of 30mm and 90mm sides for the two cases. They were arranged to an areal density of 25% for both cases.

Visualized images are shown in Figs-6 (a) and (b). For the 30 mm cube case, only a 6 m/s updraft made a clear swirl flow. Lower updrafts, however, could not make any clear swirl flows. For the 90 mm cube case, a pair of Karman vortices was observed at lower updraft speeds. As the updraft increased, one of the alternate vortices whose rotational direction was identical to the shear direction of the non-uniform flow was enhanced.

Characteristics described in this and previous sections show that it is necessary not only to supply circulation to the confluence region but also enough updraft to form a tornado-like
flow. These results suggest that forming of tornado-like flow depends on the helicity in the flow field.

Figure 3: Flow visualization of tornado-like flow for various swirl ratios (without roughness blocks)
<table>
<thead>
<tr>
<th>Swirl ratio</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vortex type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Church 1979</td>
<td>laminar</td>
<td>turbulent</td>
<td>2 cell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re = 10^5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monji 1985</td>
<td>laminar</td>
<td>turbulent</td>
<td>2 subsidiary vortices</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re = 3 × 10^4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 sub.</td>
</tr>
<tr>
<td>Present study</td>
<td>laminar</td>
<td>turbulent</td>
<td>expanded core</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re = 9 × 10^4</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Figure 4:** Shape of vortices and swirl ratio
(with results by Church, 1979 and Monji, 1985)

![Flow visualization of vortices](image1.jpg)

(a) updraft: 1m/s  
(b) updraft: 2m/s  
(c) updraft: 3m/s  
(d) updraft: 4m/s  
(e) updraft: 6m/s

**Figure 5:** Flow visualization of vortices with horizontal shear flow for various updraft speeds
VELOCITY MEASUREMENT EXPERIMENT AND ROUGHNESS EFFECT

The tangential component of the tornado-like flow was measured using laser Doppler velocimetry (LDV) for two swirl flows. One is the case of \( S=0.14 \) (vane angle 20 degrees) and another is case of \( S=0.65 \) (60 degrees). The circulation was supplied using guide vanes for these cases. Roughness blocks were uniformly arranged on the floor of the confluence region. The blocks were 5mm cubes. Three cases of their areal density, 0, 4% and 25%, shown in Fig-7 were tested.

Results of the measurements are shown in Figs-8 and 9. The abscissa indicates the distance from the simulator center, and the ordinate indicates the height above the floor. The measured velocities were the tangential components.

Overall tangential wind speeds for \( S=0.14 \) show less than that of \( S=0.65 \). That is because the tangential component at the incident flow for \( S=0.14 \) was less than that of \( S=0.65 \). As the simulator was axially symmetrical, axisymmetric flow should be expected, but some asymmetricity were observed in the measured records.

Figures 8 (a) to (c) show the distribution of tangential flow for \( S=0.14 \). Their roughness areal densities were 0%, 4% and 25%, respectively. For areal density 0%, high wind speeds were observed near the center line of the vertical sectional plane. The corresponding visualization image in Fig-3 (c) illustrates a slender core.

For areal densities 4% and 25%, high speed regions appeared away from the center. These results suggest that the turbulence thickened the core size. Wind speeds for areal density 25% showed lower values near the floor area than those for areal density 4%, and the high speed area moved to a higher position.

Figures 9 (a) to (c) show the distribution of tangential velocities for \( S=0.65 \), for roughness areal densities 0%, 4% and 25%.

For all cases, the maximum tangential velocities appeared at around 20 mm from the center. The distance seemed to be unaffected by roughness. For high swirl ratio, the swirl flow was broken and turbulent even for the smooth floor case. Wind speeds near the floor decreased with increasing roughness density.

Monji (1986) conducted visualization experiments and suggested that the vortex core expanded as the swirl ratio increased and the effect of roughness was weak for high swirl ratio. The present results agree with Monji's results.

A mathematical model of a tornado-like vortex, called Burgers vortex (Burgers, 1948), is described as,
\[ v = \frac{\Gamma}{2\pi r} \left( 1 - \exp\left(-\frac{\gamma}{4\nu} r^2\right) \right) \]  

(3)

where \( v \) is tangential velocity at distance \( r \), \( \Gamma \) is circulation, \( \nu \) is kinetic viscosity and \( \gamma \) is a scale parameter. The length scale of a vortex core can be estimated as \( 2\sqrt{\nu/\gamma} \).

If eddy viscosity can be used instead of \( \nu \), the results of the present experiments can be interpreted as follows. Floor roughness produces turbulence that increases eddy viscosity and size of vortex core. When swirl ratio is low and flow is laminar, turbulence significantly affects vortex properties including eddy viscosity. When swirl ratio is high enough, the vortex becomes broken and turbulent. Swirl flow is not affected by roughness and turbulence.

(a) plan area density: 4%  
(b) plan area density: 25%  

**Figure 7: Arrangement of roughness blocks**

(a) plan area density: 0%  
(b) plan area density: 4%  
(c) plan area density: 25%  

**Figure 8: Tangential component of wind speed (\( \theta=20 \text{ deg.}, S=0.14 \))**
CONCLUDING REMARKS

The effects of swirl ratio and applied flow have been investigated using a tornado simulator. Through visualization experiments, 1) the relation between the appearance of the tornado-like flow and swirl ratio and 2) the effects of non-uniform incident flows were investigated.

In low swirl ratio conditions, the swirl flows formed laminar tornado-like vortices. With increasing swirl ratio, the laminar swirl flow started to break from the upper part of the vortex. Finally, the tornado-like vortices became turbulent under higher swirl ratio conditions. These situations agreed with previous researches.

Horizontal shear flows and flows over non-uniform distributed roughness were applied as incident flows to the confluence region. In these cases, without guide vanes, tornado-like vortices were observed. It was noted that high updraft was necessary to form stable swirl flows.

The tangential velocity of tornado-like flow was measured by laser Doppler velocimetry (LDV) by which reverse flow can be measured. The measurements were conducted for three types of floor roughness at the confluence region and two different swirl ratios. The core size of vortices increased as swirl ratio increased, and the effect of swirl ratio was predominant with small roughness. For high swirl ratios, the roughness did not affect the velocity distributions except at the lower part that was close to the roughness. These results have been qualitatively interpreted as the effect of eddy viscosity.

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REFERENCES


