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C. T. Hsu
Iowa State University

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SYNOPSIS: Iowa ranks fifth in the nation for the annual tornado frequency per area. Although solutions for avoiding tornado formation are rather remote, if not impossible, understanding this formation process and its mechanism of operation must be advanced first. Current theories are still unsatisfactory and inadequate. A new concept of tornado modeling, resulting from extensive tornado literature studies and swirling rocket nozzle flow research, is proposed here. Based on this concept, the Iowa State University tornado-simulation wind tunnel is designed for better simulation of tornado flow.

THE PRESENT STATE OF KNOWLEDGE

Current theories of tornado formation have not won general acceptance. The combined version of these theories is summarized from a recent government publication (U.S. Dept. of Commerce, 1970) as follows:

It is more probable that tornadoes are produced by the combined effects of thermal and mechanical forces . . . The thermally induced rotary motion is the result of forces set up by the imbalance created when cool air overrides warm air. The imbalance is compensated by rapid upward convection from the lower layers of warm air, which becomes a rotary flow and forms the tornado vortex. Some mechanical, external force further constrains slowly rotating air currents. As the radius of rotation lessens, the speed of rotation increases . . . Ultimately, these converging, accelerating, rotary winds set up the tornado vortex.

The above description of tornado formation is rather vague. This statement implies that tornadoes are generated from the ground layer. However, it cannot explain complicated phenomena observed by many eyewitnesses.

Direct observations of tornado activities have been made by Fujita (1958, 1959, 1971), Goldman (1965), Hoecker (1960), and many others. Without a well-established theory, many tornado phenomena are still unexplainable; e.g., while most eyewitnesses described the action of the tornado wind as being one of suction, several felt that it was just opposite, e.g., like water spray (Hoecker, 1960) from a hose hitting the lawn, fireplace ashes blown (Hoecker, 1960) out into the house when all windows are closed, and objects screwed into (Gutman, 1957) the ground (also true for Charles City Tornado, Iowa, 1969). Although the suction phenomena accompanying a tornado are well understood, the mechanism for both the suction and the blowdown phenomena cannot be explained by the conventional theories.

Theoretical Models

Theoretical investigation of tornado flow fields briefly mentioned here are those of Gutman (1957), Kuo (1966, 1967), Whipperman et al. (1969), and Dergarabedian et al. (1967). The first two authors make use of criteria of unstable temperature stratification and pre-existence of basic vorticity to obtain "one-cell" vortex flow and "two-cell" vortex flow solutions, respectively. The condition of unstable temperature stratification which has been successfully used to predict tornado warnings serves as the energy source in order to produce the updraft velocity near the ground. However, updraft velocity can also be obtained without using the unstable temperature stratification: Whipperman et al. (1969) numerically integrated exact flow equations by imposing a tornado-like vortex, intensifying only with time, on the upper boundary. In this author's view, Whipperman's analysis has demonstrated the key point that the suction force experienced on the ground surface is induced by the vortex motion in the air, although their mathematical model may not have been physically realistic.

Laboratory Simulation

Tornado-simulation facilities are in existence at the Catholic University of America (Chang, 1969), the Severe Storm Laboratory (Ward, 1970) in Norman, Oklahoma, and the University of Kansas (Muirhead and Eagleman, 1971). At these facilities, the vortex is essentially produced by sucking air into a rotating screened cage and then discharging it through an exhaust fan or to a vacuum pump installed above the vortex chamber. Note that these vortex flows are sucked from the ground surface. These facilities can neither simulate the suction force which is supposedly induced by the swirling motion of the vortex funnel hanging in the air nor can they simulate the previously mentioned "blowdown" phenomena of the tornado activity.

THE PROPOSED TORNADO MODEL

Since the conventional theories of tornado formation and tornado mechanism are believed unsatisfactory, the following tornado model is proposed: (1) the warm moistened air is lifted up to form the cumulus clouds by the buoyancy force existing in a thick atmospheric layer having an unstable temperature stratification; (2) in these cumulus clouds, strong vortices are produced due to violent vertical shears such as those caused by the interaction of cold and warm fronts; (3) these vortices may be discharged downward in a converging shape as visible funnel clouds due to some unknown pressure gradient. For example, Rayleigh's principle does indicate that cooling of these warm clouds may increase the total pressure head; and (4) circulating motion and suction force of the ambient atmosphere is thus induced by this swirling jet.

Although the tornado funnel cloud (moisture condensation boundary) usually appears as a converging shape, the actual

[1] Department of Aerospace Engineering and Engineering Research Institute, Iowa State University, Ames, Iowa

shape of stream tubes of this funnel has not yet been authenticated, either by direct observation or theoretical prediction. According to the inviscid swirling flow theory (Hsu, 1971), if the funnel stream tube is convergent (see section 3.2, "Convergent or Convergent-Divergent Nozzles," for evidence), the swirling, or tangential, velocity increases linearly with the decreasing radius of this stream tube, and *reverse* (or suction) flow may be induced near the vortex axis. This is because the kinetic energy available for axial motion may decrease due to the increase of swirling energy, e.g., for an adiabatic flow process. The continuous loss of axial momentum, or energy, in a convergent stream tube may cause continuous reduction of mass flow rate, thus inducing the reverse flow. This possibility of reverse flow coupled with the low pressure vortex core due to centrifugal pressure reduction may be the cause of the high intensity of suction force occurring in a tornado storm. It is also possible that the axial motion of a swirling flow can be brought to a complete standstill for a sufficiently large stream tube contraction ratio. Therefore, this funnel may retract upward or travel downward depending on the pressure gradient and stream tube contraction ratio. When the funnel tip is hanging in the air, it produces suction force. When the funnel touches the ground, it may screw objects into the ground (Gutman, 1957) or blow fireplace ashes away (Hoecker, 1960).

The main difference between our proposed model and the previous ones is that the present model considers the downward traveling, swirling jet as the vortex source whereas most scientists believe the vorticity is generated from the ground surface. Because of the inadequate understanding of the nature of tornadoes, laboratory study of simulated tornado flow is necessary.

DESIGN OF THE ISU TORNADO-SIMULATION WIND TUNNEL

The proposed ISU tornado-simulation wind tunnel is shown in Fig. 1. It is composed of the following three main parts:

Vortex Generating Chamber

Three types of vortex flows are to be generated: a forced vortex (solid body rotation), a free vortex (irrotational circulating flow) and a combined Rankine vortex (a forced vortex core and irrotational circulating flow outside the core). A natural tornado funnel flow is close (Hoecker, 1960; Kuo, 1966) to the latter type.

For producing a forced vortex flow in the nozzle (Norton, Farquhar, and Hoffman, 1969), compressed air is led through many small holes uniformly drilled on a rotating disk. This disk is rotated by an external variable-speed motor. For producing a free vortex in the nozzle, the disk will be replaced by a hollow shaft of small diameter. Free vortex flow will then be produced by injecting compressed air out of radial holes on the hollow shaft while the shaft is rotating. For producing a combined Rankine vortex at the nozzle exit, either of the above two methods may be utilized. For the forced vortex flow at the nozzle exit, the nozzle flow will provide the central core and surrounding air will provide the irrotational circulating flow outside of the core. This type of flow will be used to simulate a tornado flow. In this case, the outer edge of the nozzle-exit jet stream tube is the locus of maximum tangential wind speed. For a free vortex flow, the central core near the nozzle axis is essentially a forced vortex due to the effect of viscosity. The maximum wind speed occurs at the core radius. This type of flow will be used mainly for other swirling flow research (Hsu, 1971; Batson and Sforzini, 1970).

Water vapor may be mixed with the compressed air upstream to simulate moist tornado clouds and produce the visible funnel shape.

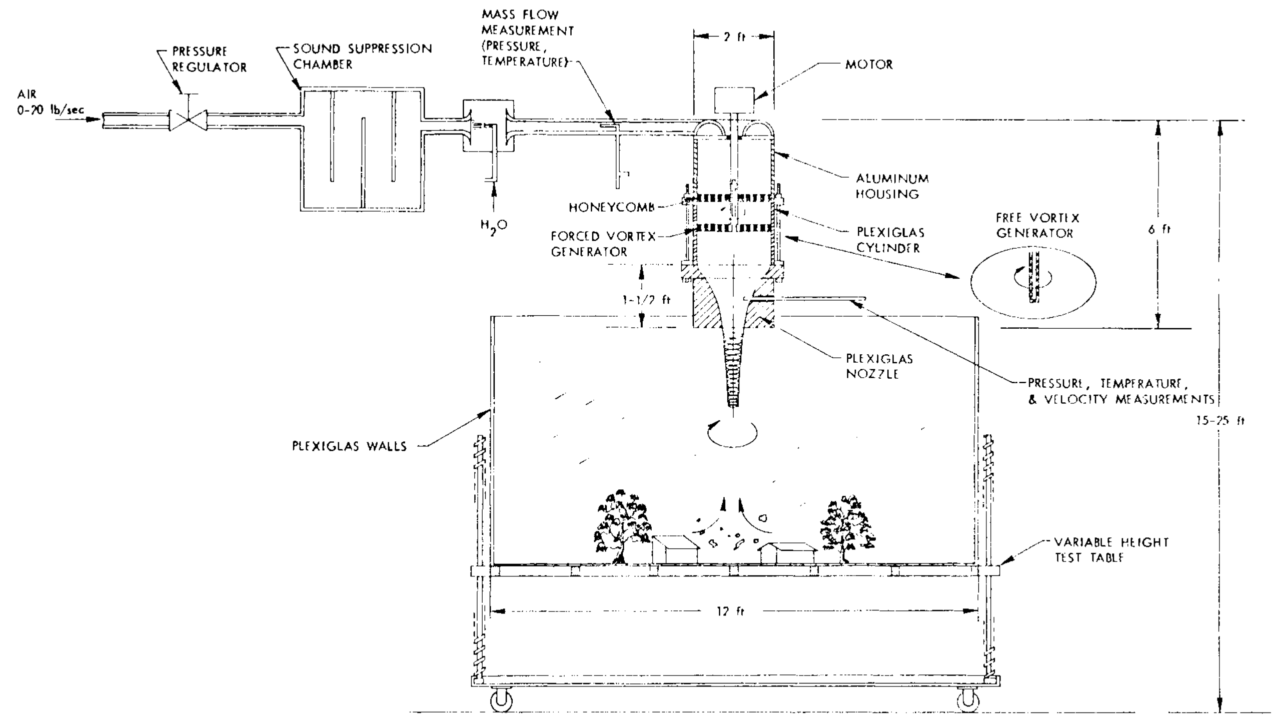
Convergent or Convergent-Divergent Nozzles

For tornado research, convergent nozzles with different contraction ratios are attached to the vortex chamber, and subsonic axial velocity is produced at the nozzle exit. Note that a convergent funnel shape is important to intensify (Hsu, 1971) the high swirling velocity, therefore producing high suction force on the ground. A description of a Texas tornado by an airplane pilot states that the angular swirling velocity of this tornado was about 500 rpm near the cloud base and about 1200-1500 rpm at the lower portion. Observations of more tree damages in the valley rather than on the plateau area in a South Hill tornado (Kentucky, April 17, 1971) by Fujita and Tecson (1971) also confirm the present converging jet stream theory. For swirling flow research in rocket nozzles, a convergent or convergent-divergent nozzle is attached to the chamber to produce choked mass flow at the nozzle throat. Thus, this facility will serve the dual purpose of investigation of swirling flow inside a rocket nozzle and tornado flow outside the nozzle.

Simulation Chamber

This chamber is large enough to simulate the open space between the tornado clouds and the surface of the earth. The axial and tangential speeds of the swirling jet may be controlled by its back pressure and the motor speed, respectively, so that touchdown or retreat of the tornado funnel can be simulated. The ground plate may contain a water pan heated underneath in order to simulate the ascending moistened air. A waterspout may be produced by placing a large water tank on the ground plate. The ground plate is able to travel at reasonable speeds. Gust winds may be produced by utilizing fans or propellers.

The vortex chamber, nozzle and simulation chamber are made of plexiglass such that swirling flow originating from the vortex chamber may be visualized (Batson and Sforzini, 1970) by injecting a colored soap bubble solution and a kerosene paint pigment mixture or by smoke or particulate matter. Dust powders, small debris particles, light structural buildings and water tanks placed on the ground plate may also be visualized as they are sucked up or blown away by the swirling jet. We are particularly interested in the interaction of this descending swirling stream with the ascending dust stream since this motion observed by investigators has not yet been considered in any existing theories and laboratory facilities. Velocity and pressure distributions in the entire flow field may be measured by standard equipment. After the construction of this proposed tunnel, our immediate action is to demonstrate the strength of suction force, supposedly produced by a converging jet of high swirling intensity. For example, the Atomic Energy Commission is particularly concerned with this suction force acting on a nuclear reactor and spent-fuel housings.



OBJECTIVES AND EXPECTED SIGNIFICANCE

The objective of this proposed wind tunnel facility is to better simulate a tornado flow. This proposed design is an outgrowth of a new concept resulting from the study of swirling flows (Hsu, 1971) in rocket nozzles. There are several basic differences from the conventional models (Chang, 1969; Ward, 1970; Muirhead and Eagleman, 1971):

- The proposed facility utilizes the principle that the suction force occurring on the ground in a tornado storm is induced by the swirling motion of a vortex funnel whereas the conventional models utilize artificial exhausting fans or vacuum pumps.
- The proposed facility blows air downward so that many unexplainable phenomena such as objects screwed into the ground, fireplace ashes blown out into the house, etc., can be easily explained, whereas the conventional models can only suck the air up.
- The proposed facility is able to simulate the interaction of the descending swirling streams with the ascending dust streams whereas the conventional models can only produce the ascending motion.
- The proposed facility is able to simulate the converging shape of a tornado funnel, which is believed essentially important to intensify (Hsu, 1971) high swirling velocity and high suction force on ground structures whereas the conventional models usually produce a cylindrical or an inverted converging shape for a tornado funnel.

It is thus believed that the present model will simulate much better tornado flow phenomena in the laboratory. To this investigator's knowledge, this is the first tornado-simulation wind tunnel of this type ever proposed.

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