The Carbonated-water Tornado Vortex

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Current theoretical descriptions of tornado vortices (e.g., Gutman, 1957) agree that their formation is related to the concentration of pre-existing angular momentum by convective processes. There is extensive literature dealing with methods of modeling this phenomenon, but we shall refer here only to several of the more recent papers, reporting experiments in which strong vortices are formed in rotating tanks of water by various means. Long (1956, 1958, 1961) investigated the vortex formed by withdrawing fluid from the center, and Morton (1963) has simulated the convection by injecting buoyant fluid along the axis. We believe that a more realistic modeling may be achieved by the release of gas bubbles in carbonated water. Buoyancy is produced in this case by changes of phase in the fluid itself, and no mass need be added to or extracted from the system. This process is also closely analogous to the release of buoyancy by condensation in the atmosphere.

The experimental procedure adopted is as follows. A cylinder containing ordinary commercial carbonated water is placed on a turntable and set into solid rotation at 90 rpm. Two sizes of vessels have been used, a one-liter beaker containing one bottle of soda, and a 6-inch diameter by 18 inch deep plastic cylinder containing 6 quarts. Carbonated water is bottled at an excess pressure of about 3 atmospheres, and therefore contains a 300 per cent super-saturation of CO_2 gas. The water has been thoroughly filtered before charging, however, and the bottles well cleaned, so that very little gas bubbles off when a bottle is uncapped. Provided the experimental vessel is clean, most of the gas survives the filling and acceleration. (It is even more satisfactory to conduct experiments in the original quart bottles, except that the optical properties are not good for photography.)

When suitable nuclei are introduced into the carbonated water, vigorous effervescence occurs as bubbles

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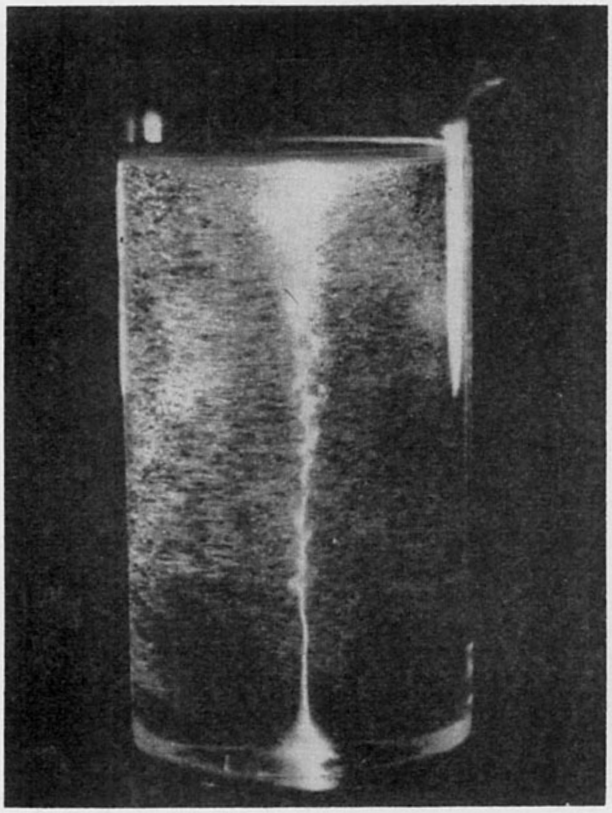

Fig. 1. Showing the intense central vortex formed when carbonated water in solid rotation is nucleated with small particles to release gas bubbles.

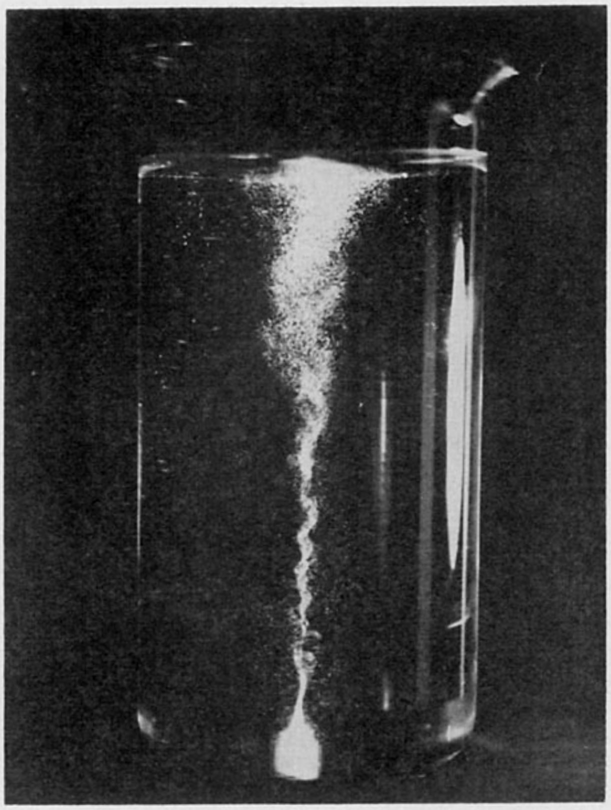

Fig. 2. A vortex in carbonated water, showing the helical structure which is often observed.

come out of solution onto the nuclei, and shortly afterwards a central vortex is formed. The exact nature of the phenomenon observed depends greatly on the number, position, type, and especially the size of these nuclei, and on the amount of gas remaining in the water.

If small nuclei of common salt are put in at the top, the vigorous convection set up here prevents the particles from falling to the bottom of the rotating vessel. A strong vortex containing bubbles will grow down from the top to the bottom of the beaker, but this does not remain attached to the bottom, although the lowering of pressure at the center of the vortex may possibly promote the release of gas there even in the absence of nuclei. When heavier particles are dropped in the top (for example, larger salt particles or coarse grained detergent powder) some of these find their way to the center of the bottom and a vigorous, nearly steady vortex seems to appear suddenly at all levels and remains attached to the bottom until the nuclei have all dissolved.

Typically, the visible region of the latter type of vortex is conical near the bottom, narrower in the middle, and spreading out in an inverted cone near the top (see Fig. 1). With large numbers of nuclei and a large amount of gas in solution the vortex may be quite regular and thick, up to 0.5 cm in diameter, and often 2 or 3 will bepresent at this stage, perhaps centered over clusters of nuclei on the bottom. As the nucleating agent dissolves or the gas super-saturation becomes less, the vortex becomes thinner and more rope-like until just before breaking up it is a slender filament of bubbles. Frequently this filament becomes twisted into a helical shape, as shown in Fig. 2, and in this case waves of alternate compression and expansion of the helix appear to pass downwards through it, rather like longitudinal vibrations of a loosely coiled spring. The bubbles surrounding the vortex in these two figures are probably moving upward more-or-less independently of the vortex circulation.

Still larger particles (for example, pieces of lump sugar or Alkaseltzer) dropped onto the bottom can still produce vortices, even though there is no direct release of buoyancy above. This is especially effective when the nuclei are constrained to fall at the center of the base, though the result is not as vigorous as when convection is present above as well.

In considering the implications of these results to the atmosphere, the most important condition seems to be the presence of a convectively overturning region above. This is consistent with observations of all tornadoes and most waterspouts and also with the energetics of Gutman's theoretical solution. The presence of unstable air near the ground, and condensation in the vortex, contribute to the persistence and intensity of the vortex but it is possible to form one without it. Convection solely from an unstable region near the ground can also form vortices, probably less vigorous ones (e.g., dust devils).

The mechanism of formation seems to be a concentration of the mean angular momentum by an inflow to the center of the vortex near the bottom boundary as a result of a decrease in pressure. This produces an increased velocity of circulation in the center of the tank, and there is probably at the same time a decreased circulation in a divergent region above the vigorous convection.

Further ideas about the production and influence of a strong region of convection some distance above the ground may be obtained by experimenting in a deeper tank. Because of the combined effects of gravity and rotation, a gas bubble released anywhere on the bottom will spiral inwards normal to the equipotentials of effective gravity and finally at the top come close to the center. It is observed in these circumstances that large nuclei placed *anywhere* on the bottom of the rotating tank of soda-water can set up a strong vortex at the *center*, not now linked to the position of the nuclei (but still maintained more vigorously if nuclei are present there as well). This process may sometimes be effective in concentrating convective activity in an already rotating region from a large source at lower levels to an intense upcurrent higher up.

It is clear that convection experiments in rotating fluids should always be carried out with light fluid rising through heavier surroundings. They cannot be reversed (as is often done for convenience in non-rotating "thermal" or "plume" experiments), because the influence of a strong rotation will be quite different in the two cases. The presence of a light core can certainly have an important effect on the stability of a vortex (Turner, 1957).

Finally, the importance of the high-level convection can be demonstrated independently of the release of instability in the vortex itself by doing similar experiments in tap water. Convection without the release of extra mass may be simulated by bubbling air from a fine tube pushed down the center of the tank from above. With a suitable depth and strength of bubbling, and therefore a certain intensity of "convective" motion in the water at the top of the tank, an intense steady vortex can be formed extending right to the bottom. This is strongly linked to the flow of bubbles above; as the bubble stream rotates, the whole vortex follows it round. The rotational velocities can be measured by introducing small particles into the flow, and we have in this way found angular velocities near the center which are 10–12 times that of the cylinder.

A vertical circulation is also present in this vortex, and is easily observed by introducing particles and colored tracers into the flow. In the experiment pictured in Fig. 3, crystals of potassium permanganate placed near the center of the bottom show that there is a converging region of upward flowing fluid along the axis. The fine filament of dye at the center often has bulges and traveling bead-like waves on it, as well as the spiral motions observed in the experiments previously described. Dye introduced at the top of the tank shows that the flow is downward in an annular region surrounding the upward flow; eventually this downflowing dye reaches the bottom, turns inward and moves up the center. A similar pattern may be observed in the carbonated water vortex. This circulation is very like that described by Rosenzweig, Ross and Lewellen (1962) for a vortex produced in a cylinder with tangential injection and axial withdrawal at the bottom, except that in their case there is another ring of vertical motion, corresponding to an outer ring of upward flow outside the dark band in our Fig. 3. No evidence of a stable flow of this kind has been observed in our experiments. The differences must be due to the different axial boundary conditions imposed on the two flows; in both cases the interaction with the end boundary layers is very important.

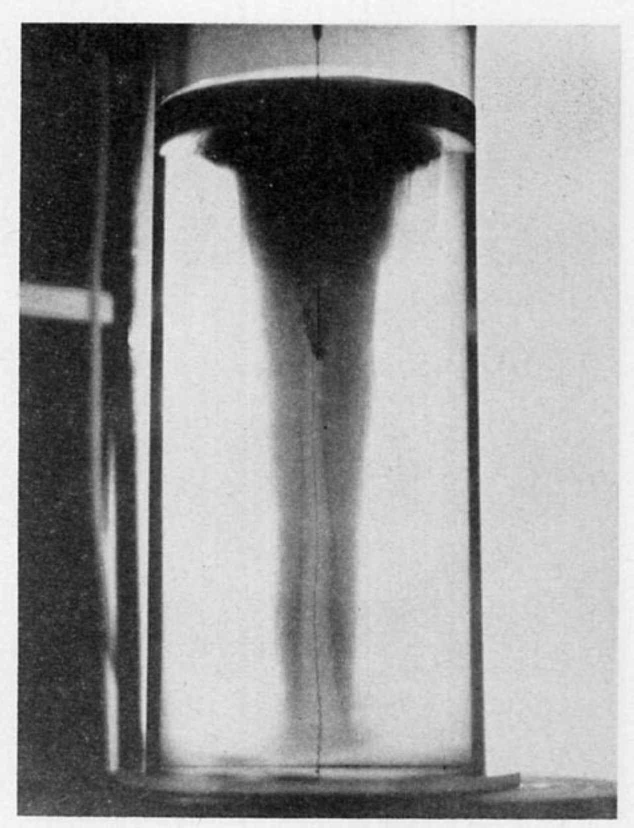

FIG. 3. Illustration of the vertical motions in a vortex, in this case formed by bubbling air near the top of a rotating cylinder of tap water. Dye has been injected at the center of the top, and a crystal of the dye placed on the bottom.

Thus it appears that all the convective motions are self-contained within the ring of downflow. This implies that, because of the stabilizing effect of the rotation, it is easier for the fluid supplying the core to move vertically near the vortex rather than horizontally from further away near the bottom. It is therefore another demonstration of the general principle established by Taylor (1921). The fluid in this central region never reaches the side walls in our experiments, and there is hope that the laboratory observations will not depend very critically on the presence of the container or its width; this indeed seems to be borne out by the few experiments so far carried out in a large tank.

Some of these observations of the appearance of the laboratory vortices are very similar to the complex core structures which have been reported for tornadoes and waterspouts [see for example the review article by Hurd (1950)] and they seem worth a more detailed comparison.

REFERENCES

Gutman, L. N., 1957: Theoretical model of a waterspout. *Izv. Akad. Nauk, SSSR* (geofiz. ser.), **1**, 79–93.

Hurd, W. E., 1950: Some phases of waterspout behavior. *Weatherwise*, **3**, 75–82.

Long, R. R., 1956: Sources and sinks at the axis of a rotating liquid. *Quart. J. Mech. and appl. Math.*, **9**, 385–393.

——, 1958: Vortex motion in a viscous fluid. *J. Meteor.*, **15**, 108–112.

——, 1961: A vortex in an infinite viscous fluid. *J. fluid Mech.*, **11**, 611–623.

Morton, B. R., 1963: Model experiments for vortex columns in the atmosphere. *Nature*, **197**, 840–842.

Rosenzweig, M. L., D. H. Ross and W. S. Lewellen, 1962: On secondary flows in jet-driven vortex tubes. *J. Aerospace Sci.*, **29**, 1142–1143.

Taylor, G. I., 1921: Experiments with rotating fluids. *Proc. Roy. Soc. A*, **100**, 114–121.

Turner, J. S., 1957: Buoyant vortex rings. *Proc. Roy. Soc. A*, **239**, 61–75.