Dyson Day Outreach Activity: Tornado Experimentation

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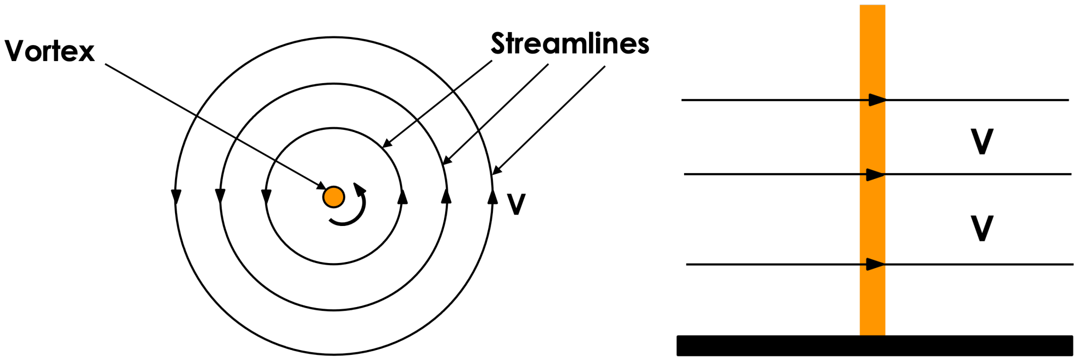
Introduction

The outreach activity aimed to give the students an insight into the three main aspects of the project. Firstly, the project involved a literature review and the development of a theoretical understanding of the mechanics of tornadoes. The fluid mechanics of tornadoes is a complicated subject hence it was difficult to explain these concepts in a way that could be understood by the students who were from years 9, 10 and 12. Secondly, the students were split into groups of 3 or 4 and tasked with the design of an experiment that would explore some aspect of tornadoes that they found interesting. This activity was followed by a brief overview of the experiment designed for the fourth year project. Finally, some results from the project were shown.

Part I: Theory



(a) Top View (b) Side View

Figure 1: Top and side views of a tornado

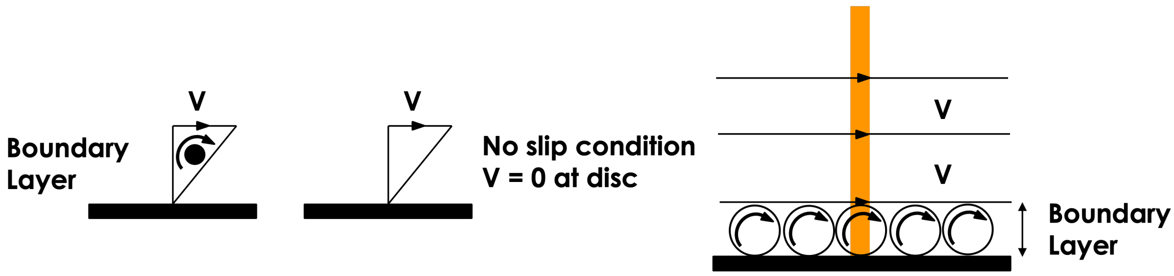


Figure 2: Boundary layer due to tornado flow

The fluid mechanics of tornadoes is a broad and challenging subject and, in the outreach day, the question of what 'powers' or sustains a tornado was put to the students. This question was the topic of the first part of the presentation and aimed to link some aspects of tornado (or vortex) flow with some familiar concepts to the students, including circular motion and the no slip condition.

Tornadoes are an example of atmospheric vortices and hence the definition of a vortex was firstly presented. A vortex causes rotation of the flow and we can illustrate this motion by sketching circular streamlines around the vortex core. Figure 1a shows a top view of a tornado, illustrating the flow it induces. Now, if we consider a side view of the tornado, we would see a structure as in figure 1b, with the rectangular vertical structure being the tornado and the streamlines showing the circular motion around the tornado core at different heights.

The no slip condition was then introduced to the students. The velocity of the fluid must be zero at the surface as the ground is stationary. This means that we have a linear increase in velocity near the surface, as shown in figure 2. This region of linearly increasing velocity is known as a *boundary layer*. The velocity gradient indicates the presence of *vorticity* and this effect can be modelled as the result of a roller, as shown in the image furthest to the left in figure 2. Therefore, the boundary layer can be modelled as a series of rollers, with the bulk flow moving along these rollers at velocity V. In more technical terms, these rollers are actually small vortices and we describe this boundary layer as having *horizontally aligned vorticity*.

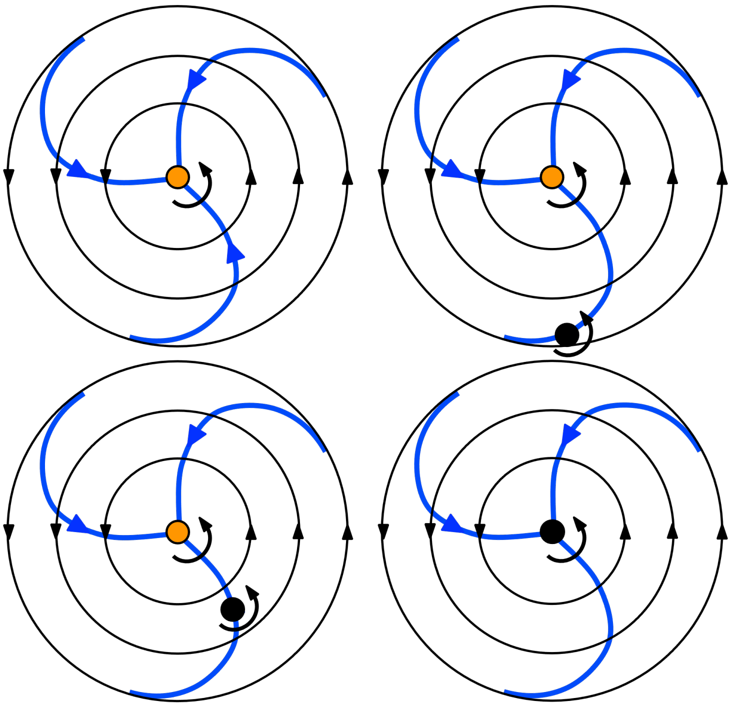


Figure 3: Illustration of the inflow in the boundary layer

The idea of objects being pulled into a tornado is almost universally recognised. An interesting aspect of tornado flow is that, due to a trade-off between centrifugal and pressure forces in the boundary layer, there is a radial inflow in the boundary layer towards the center, as shown in figure 3 by the blue lines. This means that these rollers previously described are pulled towards the center of the tornado. The first image of the figure shows the spiral inflow that arises near the ground around a tornado. The second image adds one of the rollers in the boundary layer that was previously shown in figure 2 in black. The roller is initially near the edge of the flow field. The third and fourth images show this roller getting pulled to the center of the tornado. Note how in the final image, the roller is now in the center and seems to have replaced the original orange vortex. This explains how the motion sustains itself. The tornado forms and results in the formation of these 'rollers' in the boundary layer. The tornado pulls these rollers towards the center and, eventually, the roller is aligned with the center of the tornado. This central roller is now the source of the rotation of the flow which, in turn, forms new rollers! Drawing the analogy with the rollers is a simplification of the actual mechanics however hopefully illustrated the idea that a tornado's motion is self sustaining.

In more technical fluid mechanics terms, we would say that fluid exhibiting horizontal vorticity flows to the center of the tornado, at which point it turns upwards and the vorticity is now vertically aligned, causing the tornado's circular motion. Students from years 9-12 would not be familiar with vorticity, as it is a concept introduced in higher education (second year of the Cambridge Engineering course), however the above statement is provided for completeness.

Part II: Activity - Design of tornado experiment

After a challenging introduction to the fluid mechanics of tornadoes, the second part of the activity changed the pace somewhat and involved the students working in small groups to briefly design an experiment that explored an aspect of tornadoes that they found interesting. The brief was kept open so that the students had full freedom in exploring the task.

Most students opted to design an experiment that involved small-scale tornadoes in a lab setting, as was the case in the fourth year project. These students were challenged on whether it is realistic to be able to draw conclusions from a much smaller, slower tornado flow. Similarly, the students who opted to take measurements of actual tornadoes were asked to consider why that may be difficult. Most students realised the potential danger associated with proximity to tornadoes and how a lab experiment would be more practical, given that one does not have any control over when a real tornado forms or the features of the formed tornado. A small-scale tornado in a laboratory setting allows freedom of the researcher to decide the features of a tornado (strength, speed etc.) and when they want to experiment.

All students realised that something was required to introduce rotation to the flow in a lab setting. There were several solutions to this, including stirring the fluid, drawing fluid out the bottom of a tank to form a whirlpool (like in a sink) and rotating the surface on which the tornado forms. Some students also considered the introduction of some fluid or powder to visualise the flow field. Others mentioned the use of sensors to measure the pressure in order to quantify the flowfield.

The students were also asked to think of one particular aspect of tornadoes they wanted to explore in their experiments. One student designed an experiment with a rotating disc surface and wanted to explore how the rotation of the disc compared to the rotation of the tornado. Another group was interested in the variation of the core diameter with tornado strength. Another example of an interesting research question from the students was whether one can predict the movement of a tornado by taking measurements of a tornado's trajectory. One group wanted to explore the effect of the size and number of 'rollers' in the boundary layer. In more technical terms, this is essentially exploring the effect of the Reynolds number on the tornado as increasing the size and number of these rollers, which are analogous to vortices, is similar to making the boundary layer turbulent, a topic of much interest in literature.

Part III: Vortex chamber design and flow visualisation

Now that the students had spent some time thinking about tornado experimentation, the final part of the session began with the presentation of the experiment developed for the fourth-year project. Figure 4 shows the labelled diagram of the apparatus. The operation of the experiment was explained briefly, with a pump driving flow out the top of the cylinder and inwards at the bottom, as shown by the blue dashed arrows. Upon entry to the chamber, the flow passes a foam ring which smooths out the flow. Blades then turn the flow to introduce the swirl required to form the central tornado (vortex). The cylinder and base are transparent so that we can carry out our flow visualisation studies and take other measurements.

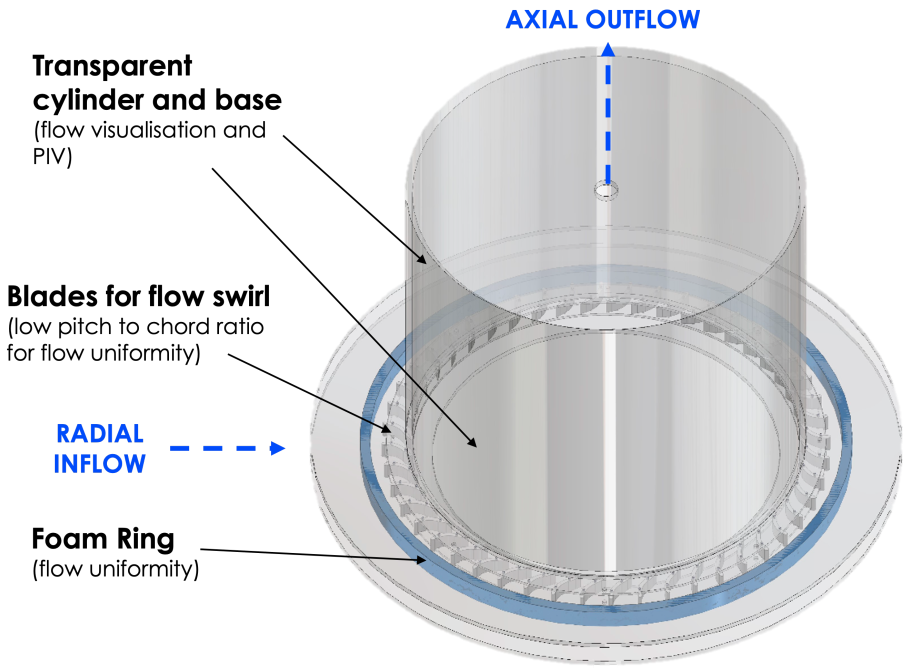


Figure 4: CAD model of the experimental apparatus

Finally, the technique of flow visualisation was introduced as the application of a coloured fluid to the flow. The dyed fluid will follow the local flow and therefore allow us to see exactly what is happening in the tornado. Some images and videos were shown of the simulated tornado using dyed milk to visualise the flow. Some comparisons between the project's flow visualisation images and real tornadoes were shown. These comparisons suggest that the experiment is representative of tornadoes, which was one of the main conclusions drawn from the project.

Closing remarks

The workshop aimed to give the students some insight into the challenging theory of fluid mechanics, an introduction to experimental fluid mechanics and some of the techniques used in research. The students' ideas from the experiment activity were impressive and they engaged enthusiastically with the activity. It is hoped that the students found this an exciting and interesting introduction of fluid mechanics.