U.S. Department of Energy

National Energy Technology Laboratory

Study of Select Gas Vortices
Or

Contents

Overview

A Word to the Educator

Classroom teachers are often challenged when trying to enhance their students' appreciation for science. Creating and refining physically large projects can be tedious, and may be hampered by the need to encompass multiple disciplines. Teachers must also keep the projects interesting, feasible, and inexpensive.

We kept these needs in mind while designing this document, and strove to demonstrate scientific principles while allowing students to learn while having fun. As a result, what we present here is not so much a lesson plan, but a lesson plan builder.

What follows is an interesting investigation of air, pressure, air velocities, and some basic electrical concepts and skills, all wrapped in an application of the scientific method titled "*Twister Anyone?*" We have included a flow chart, designed to help you to construct a lesson plan that meets your unique classroom circumstances, and information that will help you adapt the projects for various time constraints, conditions, and skills. These experiments can be performed in a general or slightly science-oriented environment, and the project can be expanded if a well-equipped laboratory is available.

These lessons are the result of a collaborative effort between two public education teachers with widely differing backgrounds and experience, and a mentor researcher from the National Energy Technology Laboratory (NETL) in Morgantown, West Virginia. This effort was driven by a collaboration of the Mon Valley Education Consortium and NETL's Educator in the Workplace program. The program is sponsored by NETL, through the U.S. Department of Energy, fosters science understanding and education.

Why study a gas vortex?

Why does NETL foster the recognition and understanding of gas vortices? Vortices are common phenomena: water going down a drain, macro and micro weather systems, swirls off wing tips, and even entertaining smoke ring are all vortices. In automobiles, the term "vortex" comes into play in the naming and internal workings of engines.

At NETL, the vortex represents a key element in advanced high temperature gas turbine combustion. Other applications of vortex action exist as well, including high-speed particle separation. NETL supports understanding of vortices, from the ever-present examples to the highly technical applications.

Project Description

These projects will guide you through building vortex generators. Different generators will result in different vortices; for example, a classic tornado vortex can be generated with thermal convection currents from a hot plate or with a mild vacuum from a small fan. If you construct a giant box or soda-bottle vortex generator, the result will be a ring vortex. The directions for each of these are included.

If you'd like to demonstrate more than one type of vortex, mix and match the sections of this document. The flow chart will guide you in tailoring the lessons to your needs.

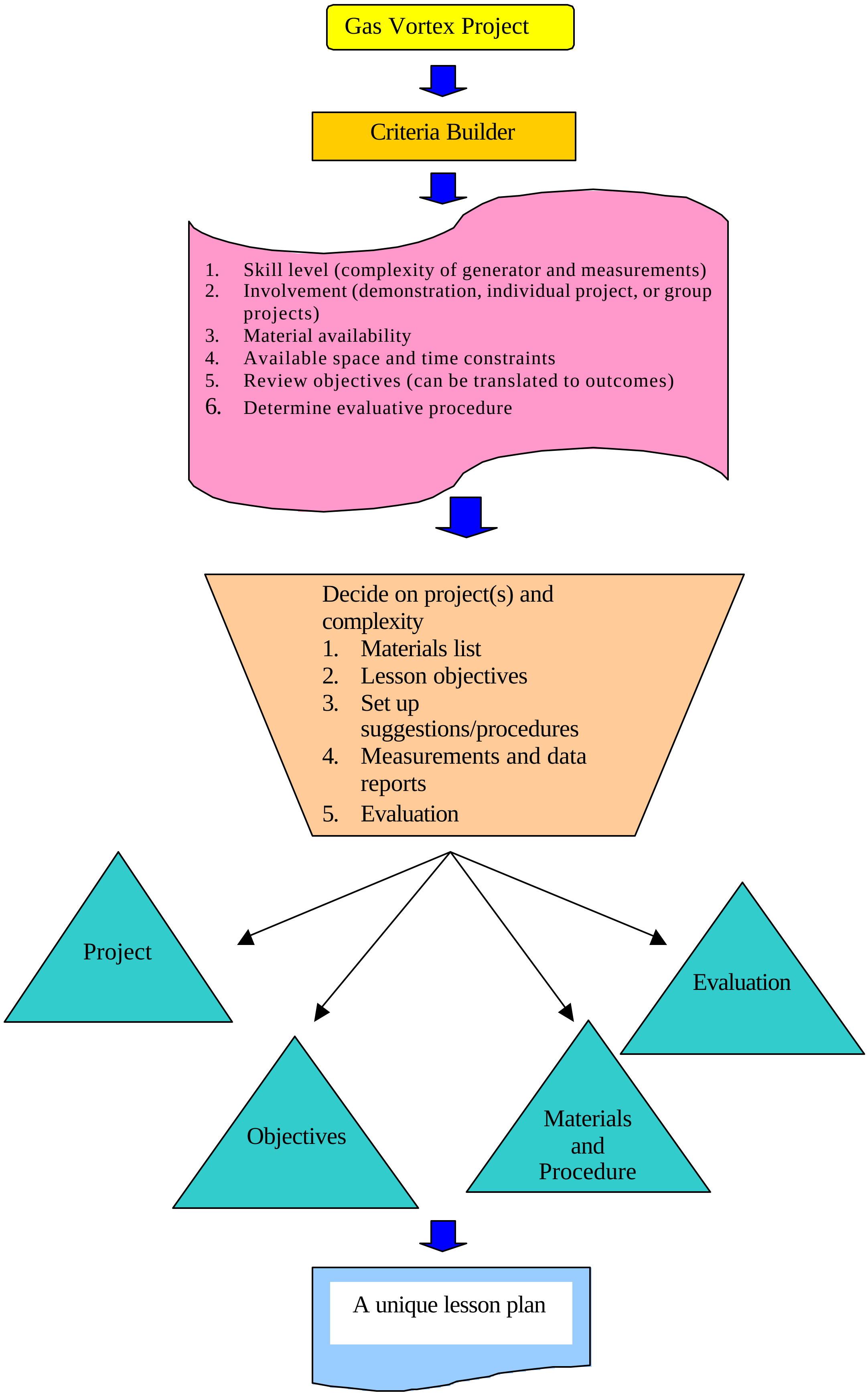
With guidance, students at any grade level can accomplish these projects, so what you build will depend on your imagination and your students' investigative skills and curiosity. High school science students will appreciate the complexity of generating and measuring vortices, while elementary students will be intrigued by vortices' appearance. With direction, all students may question vortex origins, their effects on surrounding materials, and their energy release potential.

Vortices have parameters that can be sensed qualitatively, measured, and quantified. These parameters should be considered when choosing which vortex type to investigate . To measure the parameters, you must decide what you'd like to measure, and then devise methods and apparatus to make those measurements.

The goals are to first get the students actively involved, then to have them analyze measurements, discover relationships, and describe the vortex experience.

This vortex, which was created in a tornado chamber, awes children. Students at any grade level can build a similar chamber.

Vortex Project Flow Chart



Criteria Builder

To decide which project is right for your situation, you must consider the materials required to build the generators, your lesson objectives, the amount of work required for the project, and the procedures for measuring and collecting data. Some of this basic information is provided below. More detail can be found in the specific sections of this lesson builder.

Ring Vortices

Ring vortices can be felt rather than seen, and devices can be constructed to demonstrate some of their properties. A ring vortex makes an excellent black box experiment.

Giant Box Vortex

Construction of the giant box vortex is simple, and takes less than 15 minutes once the materials are gathered. The result is a ring vortex, with the size of the vortex dependent on several parameters.

Small Vortex Ring Launcher

The launcher is constructed from soda bottles or other small containers, and can be made by groups or individuals. Some launchers will present visual smoke rings in a matter of minutes. This project is ideal for introducing students to the concept of vortices.

Linear Vortices

Although any of these projects can be used as demonstrations, linear vortices are ideal. These generators produce wonderful visualizations of linear vortices, and help achieve the ultimate goal: getting students involved and excited.

Convection Vortex

An easy-to-build convection vortex offers easy visualization of thermally produced linear vortices. They can be constructed in twenty minutes, and students can do the work themselves.

Vacuum Linear Vortex

These generators are fairly complex to build, but they offer great demonstration and complex measurement possibilities. The resulting vortices are remarkable.

General Objectives

The objectives are to construct a variety of stable vortex generators, to produce, observe, and in some cases measure the resulting properties of the vortices, and to build appreciation for air bound vortices of various types. Students will be able to overcome problems that occur while constructing the generators, and their efforts will result in stable vortices with measurable parameters. Additional objectives include promoting the use of the scientific method, while inspiring further experimentation and questions.

Specific Objectives

Ring Vortex Generator

- Experience non-visualized ring vortices.
- Devise at least two ways to detect a ring vortex without visualizing it.
- Predict some of the properties of a ring vortex prior to visualization.
- Observe the formation and properties of a ring vortex.
- Hypothesize and evaluate the effects of different geometric shapes used for the generator orifice.

Convection (Thermal) Vortex Generator

- Observe formation and properties of a convection vortex.
- Identify the conditions needed to create a convection vortex.
- Predict effects of the vortex, based on changing variables (such as lower or higher air temperatures, shorter or taller box, bigger openings in the box, etc.).

Vacuum Vortex Generator

- Observe formation and properties of a vacuum vortex.
- Identify the conditions needed to create the vortex.
- Build and apply a velocity probe (measuring device).
- Demonstrate the need to standardize measuring instruments.
- Depict collected data graphically.
- Apply data analysis techniques.

Materials and Procedures

General Materials

- Visualization material, if required for your project
- Rubber bands
- Paper clips
- Scissors or utility knife
- Tape—Scotch, duct, masking, and electrical
- A bright and directional light source
- White glue
- Dark background or paint

Please Note:
To view gas vortices, you must use a visualization aid such as water vapor, smoke, or the product of some chemical process. Regardless of visualization aid used, the background must be contrasting to render the most dramatic/pleasing effect. Since most of the visualization materials are white, black or dark backgrounds enhance the visualization greatly.

Ring Vortex Generators

Giant Box Vortex Generator

Other Materials

- A large box, ideally 20” or more on edge (bigger box = bigger vortex)
- A large plastic trash bag
- Heavy rubber bands

Figure 1. ***Giant Box Vortex Generator. Generator orifice is shown at the left, and the bellows is shown to the right, covered with a trash bag.***

Procedures

To make the generator orifice, cut a hole about 10” in diameter in what will be the front of the box. Save the piece of cardboard you have cut out.

To make the bellows, cut a larger hole in the top and toward the back of the box (see Figure 1) The hole should be larger than the orifice and roughly form a ratio of 2:3 (orifice diameter to bellows diameter). From the cardboard cutout piece you saved, cut a 6” diameter circle.

Fold a trash bag so that there are at least two layers of plastic. Lay the folded bag over the large hole and push the bag about half way into the box. The bag must be large enough to still cover the hole. Fix a handle, using any available material (large document clips work nicely), to the center of the small circular cardboard cutout. Tape the cutout to the middle of the folded trash bag. Center the handle and tape all edges of the folded trash bag (even the overlapped ones) to the box, covering the bellows hole. Attach a stout rubber band directly between the cutout and the bottom of the inside of the box.

To operate, pull the bellows up and let it go. A remarkable vortex will be generated at the orifice as the bellows collapses into the box. Although you can not see it, you can feel the air from the vortex at astonishing distances.

To understand the vortex's impact, make a curtain from string, magnetic recording tape, or other light material. These materials can also be used to demonstrate the vigor and coherence of the vortex.

To see the vortex, use smoke or other visualization material (see Figure 2). Information about visualization can be found in another section of this document.

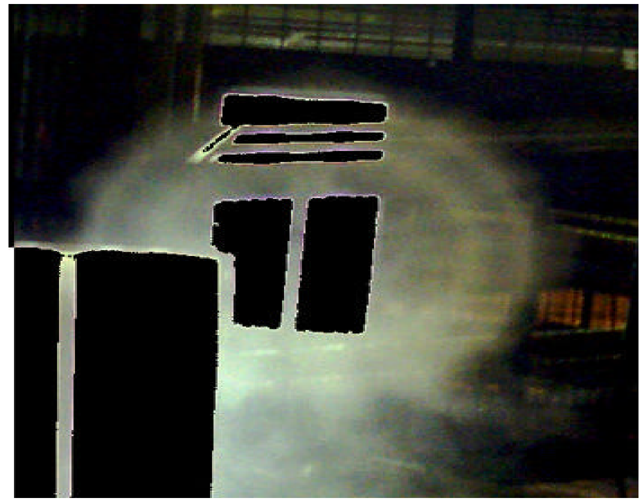


Figure 2. ***A ring vortex generated vertically and rising about 25 feet. This vortex was made visible using smoke. Note the vortex striping. (The large black squares in the picture are lights which were removed from the picture to make the vortex more visible.)***

Speed, duration, vigor, size, and variations relative to bellows activity can all be investigated. Investigations provide opportunities for students to devise ways to make measurements and present the results and conclusions.

Alternate investigations for this vortex generator can be found in *Appendix 2*.

Small Vortex Ring Launcher

Other Materials

- A 2-liter bottle or similar cylinder
  OR
- A box in which a flexible diaphragm (balloon or rubber glove) can be placed opposite a small hole

Procedures

A plastic soda bottle, squeezed just right, will generate a small vortex. A visualizing material helps in this case, since the neck of the bottle limits the force of the vortex. To generate more vigorous vortices, cut off the bottom of the bottle and put a balloon or rubber glove over the new hole.

Like the giant vortex generator, the speed, duration, vigor, size, and variations in the vortices can all be investigated. There are multiple opportunities for students to measure variables and present the results and conclusions.

Linear Vortex Generators

Convection Vortex Generator

Figure 3. *Convection vortex generator. Notice the long narrow slits on the front and side of the box. The large window is the viewing window.*

Other Materials

- Approximately 20 square feet of cardboard (15” x 48” sides)
- Electric skillet, approximately 1500 W
- A quart of water

Procedures

Studying thermal vortices is a bit more difficult than studying other types of vortices. Tornadoes are an example of thermal vortices, and few can deny their inherent defiance of close scrutiny. Yet these vortices can be generated on a small scale, with little more than an electric frying pan, some water, and a tall cardboard box.

Using heavy cardboard, construct a square chamber about 15” on a side and 4’ in height, smaller if your heat source is less than 1500 W. The bottom and top should remain open.

Along the sides, close to the corners, cut a long, narrow opening. Do this by cutting on three sides (36” x 3”) and folding the flap inward. Repeat at each corner, making sure each opening has the same orientation. Cut out a viewing port about 3’ long and 10” wide, and cover it with a transparent material. This opening will be your window to the tornado. Paint the inside of the box black to facilitate viewing.

To create the vortex, fill the skillet with about a half-inch of water and turn it on. Place the box on top. Soon the water will begin to boil and you will also have a well-formed columnar vortex—a tornado. Adjust your lighting for best viewing.

Complex Vacuum Vortex Generator

Other Materials

- Drill and bits
- Glue gun
- Soldering iron and solder
- Screwdriver
- Pliers
- Scissors
- Meter stick, or other measuring device
- Four 4” plastic pipes, 3’ long (for top frame and plenum)
- Four 3” plastic pipes (for standpipes/air directors)
- Four 3” plastic pipe caps
- Fan for the vertical pressure differential (Shop-Vac vacuum)
- Fan (Shop-Vac exhaust) for rotating the internal air mass from standpipes
- Sufficient material to enclose the structure
- Top plate (laminated cardboard pieces)
- Large, flat delivery system for fog or smoke
- Four plastic elbows T’s (for corner connectors)

Procedures

Drill holes (5/16”) two inches apart in a line along the length each standpipe. Cap one end of each standpipe.

Figure 4. *Vacuum vortex generator.*

Drill a hole about 2-2.5” diameter in one top frame pipe. Assemble the unit—it should look like a square supported by four legs. Arrange the holes in the standpipes so they all point in the same direction, slightly inward. This will direct air to swirl inside the structure.

For a top plate, laminate cardboard pieces (three or more layers). In the top plate, make a centered hole, 2” or 3” in diameter.

In rooms with very still air, the structure may be left open but for organized vortices in drafty environments, at least two sides of your structure may need to be covered completely. We used plastic drop cloths for this purpose. Covering the third side and one-half to two-thirds of the fourth side will make your generator even more successful. To create contrast with the visualization materials (which are light), use dark material to cover the sides. If the unit is placed against a dark background, use clear covering material (see Figure 4).

Fix a vacuum source to the hole at the top of the generator (see Figure 5), and a pressure source to the standpipe plenum (one or two vacuum cleaners, for example). For investigative purposes, the vacuum and pressure sources should be able to be varied in some reproducible manner. Place a large, flat box on the floor inside the generator, to dispense the visualization material slowly and evenly. This allows observation of vortex formation, and prevents the vortex chamber from filling with fog or smoke.

Figure 5. *The fan in its plenum—a two-speed stove fan mounted in a plywood box. It provides a vacuum at the top of the generator. The ruler is six inches long.*

Visualization

A visualization aid is required for viewing gas vortices. There are five viewing options for the vortices produced in these projects: steam, cool water vapor, dry ice, ammonium chloride, and smoke. Note that since most of the visualization materials are white, black or dark backgrounds enhance the visualization greatly.

Water Vapor

The easiest visualization method uses visible water vapor, which is excellent for the linear vortices in particular. For the thermal generator, vapor is supplied in the form of steam. An atomizer is a good source of cool visual water vapor, and another involves immersing dry ice in warm water—creating clouds of white fog.

Please note that water vapor causes condensation, and may present problems with projects constructed from paper products.

Caution:
The fog originating from dry ice is CO_2 gas, and does not support life. Do not allow anyone to breathe the fog.

Caution:
Ammonia and HCl are caustic!
ONLY TEACHERS should handle these materials. Keep reaction chemicals away from children!

Chemical Reaction

A chemical reaction between ammonia and muriatic (HCl) acid produces a dispersion of ammonium chloride and water vapor. The reaction results in perfect visualization material for both ring launchers and the vacuum vortices.

Please be very careful with the reacting chemicals. Although they are common, they are still **VERY** caustic. Paper towels should be placed in a vented reaction vessel to absorb the reaction materials, and this vessel should be placed in the vortex generator.

Smoke

Smoke is a wonderful visualizing agent. However, it can be a hazard without adequate ventilation. There are several good sources of smoke, the least offensive being an incense stick. A very controllable source is a theatrical smoke generator.

Measuring Air Velocity

With this plan, you can construct an electrical probe designed to measure relative velocities in a vortex. This will require some inexpensive parts, soldering materials, minimal soldering skill, and a sensitive voltmeter. There are other methods to measure gas velocities, and inventiveness is encouraged.

Probe Materials

- Bell wire
- Thermistor 250 Ohm—small, glass covered, axial for Probe B
- Thermistor 2.5K Ohm – for Probe A
- Resister 100 Ohms 0.5 W
- Voltmeter (milli-volt range required)
- Two 9 V batteries
- Two 9 V battery connectors
- 12 V solid-state regulator or
- 12 V regulated power supply of at least 0.4 mA capacity
- 3/16 dowel
- Plastic for shroud (transparency film)
- Tape, both double sided and electrical
- Ruler

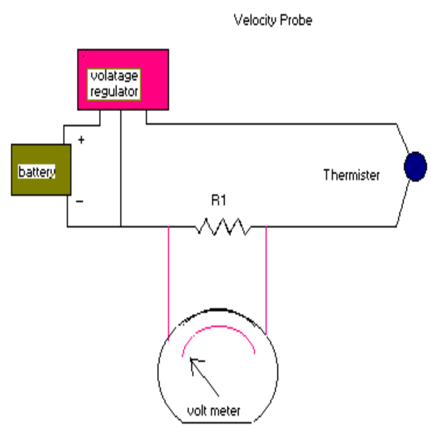


Figure 6. *Velocity probe diagram.*

The probe, which measures air velocity in the vortex, is constructed from a 250 Ohm thermistor, which is energized with a regulated 12V source. The source comes from either a variable or fixed power supply, or one constructed from two 9 V batteries in series and regulated with a standard solid-state voltage regulator. Additionally, a 100-Ohm resistor is used in series with the thermistor to measure a voltage drop. The thermistor is remotely attached to a 3/16" wooden dowel, which allows it to be positioned within the vortex chamber. The rod is marked with a measure so a reference position can be recorded. The voltage drop across the resistor R1 (see Figure 2) is recorded opposite the position of the dowel rod. In theory, the probe, although not calibrated, cools in the airflow and offers indication of air movement across its surface. The faster the air moves, the more heat will dissipate, and the current change (from the thermistor's resistance variation) will be sensed as a voltage drop across the sensing resister. Information can be plotted as position versus 1/voltage. See Appendix 5.

Testing the Probe

We built two thermistor probes. Each with a different thermistor resistance value. We found that the a larger thermistor resistance increased the probes sensitivity but made the time needed to reach a stable reading increase dramatically, Also, although 9 volt batteries and a voltage regulator can be used to energize the probe, we found that a regulated power supply from an old computer worked well .

Plug the first probe, Probe A (with a 2.5 K-Ohm thermistor), into a 12 V regulated source. The vortex generator should be set up with three sides covered and the open fourth side against a wall.

Introduce Probe A at 12” height increments across the diagonal of the chamber. Allow the voltage variance to steady before recording data. Record both control and variable data sets by repeating the experiment with the fan off and the fan on. Record the information on a spreadsheet and a graph. Repetition shows remarkable fidelity in trend but not value.

Probe B is a thermistor of different type and value. This probe allows for generation of greater heat and, therefore, a faster recovery rate. The difference in this probe will be that the thermistor is smaller, constructed from glass, and has a lower starting resistance (250 Ohms, compared with the first probe of 2500 Ohms). The voltage source is the same, but in our experiments, the Probe A took two or more minutes to calm after being moved. A warmer probe should recover quicker. Comparative data can be found in Appendix 5.

Probe B has a markedly faster recovery rate; however, it dissipates far more heat and shows a far less voltage variance. The curves from the two probes are not very different if Probe B is run at either 5 V or 12 V. The differences are inherently tied to the shape and structure of the two thermistors. The temperature variance of the probe-sensing resistor is being ignored and may indeed have some effect during load changes. Other variables were also disregarded for our purposes, but the probes demonstrate that if the experiment is conducted within a relatively short time, the data is comparable.

Many lessons can be derived from the use of the probe with the linear vortex generator. A few are listed below.

- **Elementary electrical circuits.**
  These probes introduce the concepts of circuits, circuit design to meet particular demands, and soldering.

- **Method and design of data sampling.**
  The probes can be used to introduce methods and design of data sampling, by comparing the readings of different collection methods and explaining the treatments of the results. This would involve sampling data more extensively than explained here.

- **Probe calibration.**
  Calibration of the probe was not attempted here, but could provide ample lesson opportunities.

- **Alternate observation techniques.**
  Devising appropriate alternative methods of air speed detection would be a valuable learning experience.

Appendix 1 Vocabulary

This vocabulary list includes words and phrases that may be new to students, and may be used as a primer for vortex study. We do not want to emphasize vocabulary words as objectives of the lessons rather than consequences of discovery, and do not believe learning them should be a requirement for experimentation.

Air mass
Ammonia
Ammonium chloride
Amperage
Chemical reaction
Circuit
Control
Current
Data array
Gas vortex
Horizontal
Linear vortex
Muriatic acid
Plenum
Power supply
Pressure
Pressure
Probe
Resistance
Ring vortex
Rotation
Smoke ring
Thermistor
Tornado
Twister
Vacuum
Variable
Velocity
Vertical
Visualizing material
Volt/Ohm meter
Voltage regulator
Vortex

Appendix 2 Alternate Investigations: Ring Vortex Generator

That the generator need not have a perfectly round opening begs the question*: What are the practical geometric constraints of the orifice?* Students can attempt to answer this question by studying alternate openings for the generator.

Supposition

The shape of the orifice has a direct effect on the coherence of a vortex.

Observation

To observe the vortices' travel, construct a method for visualization. Because a vortex is coherent during travel, a strip curtain can be constructed and hung in open quiet air. Note the results of a ring vortex generated at the curtain. Then, use alternate geometric shapes for the orifice.

The resulting vortices cannot be seen, but their effect on the curtain can. A coherent vortex, generated through the altered geometry of the orifice, should be able to traverse a gap. Determine this by testing a circular orifice—it will have a similar effect on the curtain. A vortex that is unstable or ill formed should not be able to traverse as great a distance, and will have little effect on the curtain. Using this method to indirectly confirm vortex formation, some limits of orifice geometry can be determined. One suggestion is to maintain a constant orifice area, regardless of the geometry.

Supposition

The volume of the gust has an effect on the speed and formation of ring vortices.

Observation

There is a limiting relationship between the volume and vigor of the gust, and the geometry of the orifice. Students should consider air volume, used to generate vortices, while trying to keep acceleration as constant as possible. Too violent a rush of air is too turbulent for vortex formation at the orifice, whereas a less forceful rush of air will generate a viable vortex. This may mean less air volume or less vigor was used to generate the gust.

One would think that the vortex must adhere to a round energy-minimizing configuration. When a vortex is created from an alternate geometry, students may be able to determine what other shapes are possible. Varying the geometry of the generator orifice will also help students understand that certain geometry and airflow combinations may prevent the formation of a vortex altogether.

Measurable items

- Effects of a vortex on the target (on a scale that differentiates between a vortex and a non-vortex effect)
- Distance from generator to target
- Velocity of the vortex
- Volume air used to generate a vortex
- Bellows vigor used to generate a vortex

Materials

- Fairly large vortex generator, with a replaceable orifice site and various orifice geometries
- A curtain of long sections of Mylar tape such as audio or video recording tape, or fine strips of paper
- Adhesive tape
- A sizable room with calm air
- Stopwatch
- Ruler/tape measure

Experimental Control

Develop a scale of vortex disturbance and determine the pattern of that disturbance to discover if a vortex is being produced. Establish a scale of volume versus distance and average velocity versus volume; this will help determine the range and effectiveness of a vortex and the characteristics of the disturbances. As a follow-up activity, conduct tests with visualization materials to verify conclusions.

Evaluation

Compare air speed, distance of effectiveness, and disturbance patterns of your original vortices to the geometry, volume, and strength of generation; this will allow you to judge the size and shape of your vortices (or non-vortices). Compare these observations with the observations from the follow-up investigation.

Appendix 3 Probes

Figures are presented so that you can see their configuration (see Figure A.1) and relative sizes. Probe B (figure A. 2) is fairly small in comparison to Probe A. The thermistor used in Probe A was about three times the size of the thermistor used in Probe B.

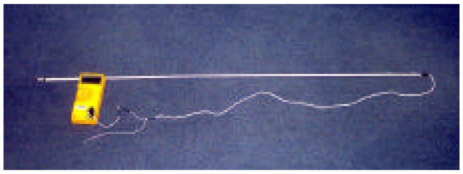


Figure A.1. ***Configuration of both probes.***

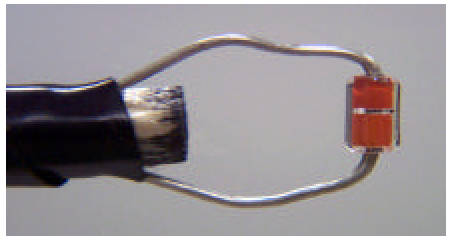


Figure A.2. ***Close-up of Probe B's thermistor***.

Data Presentation

Below are sample data collected from Probe B(Figures A.3 and A.4). Please remember that these data are not complete, and are provided here only as an example.

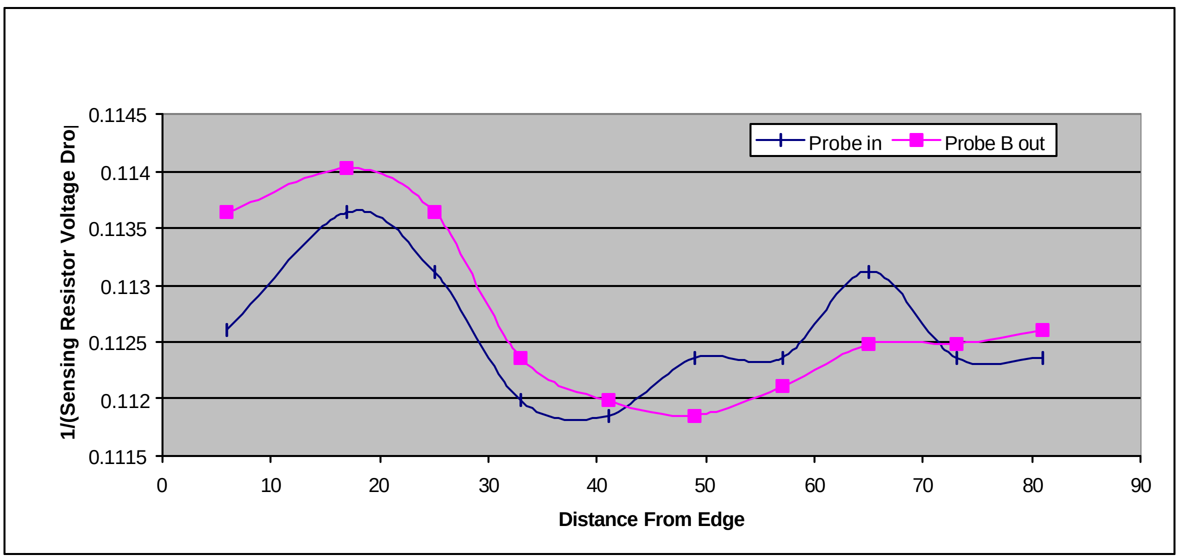


Figure A.3. *Air velocity in enclosed vortex chamber, with fan off, as measured by Probe B.*

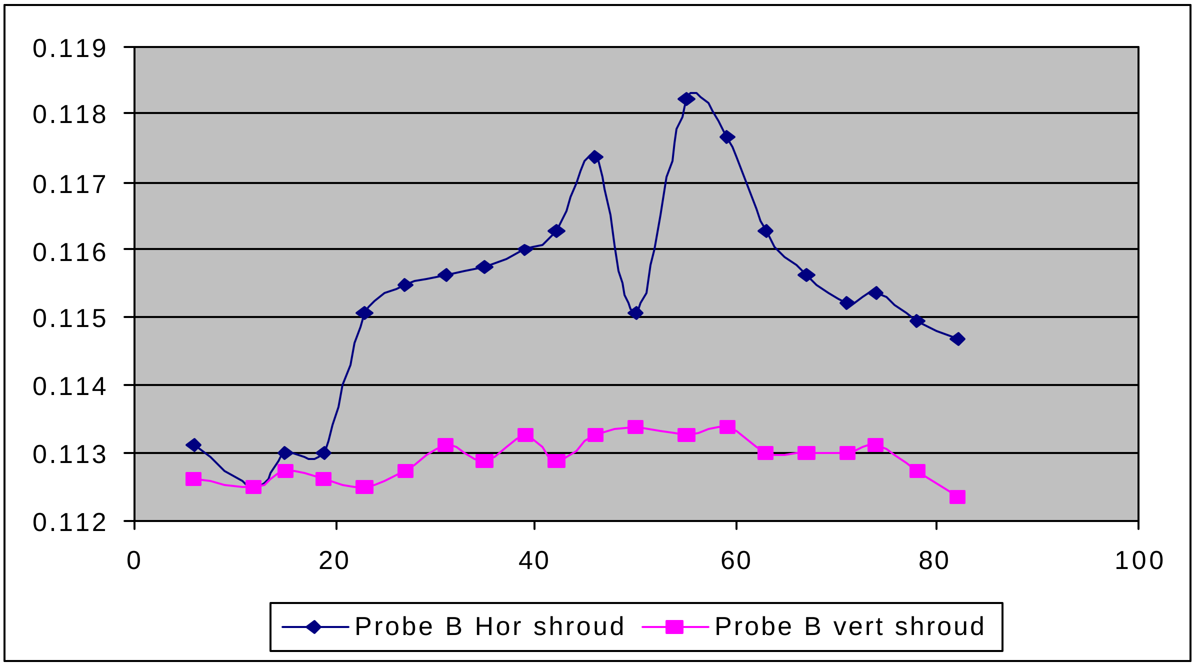


Figure A.4 *Air velocity in enclosed vortex chamber, with fan on, as measured by Probe B.*

Appendix 4 Resources

The following URLs contain more information on vortices and vortex modeling.

Applications Of Euler's Equation
http://muweb.millersv.edu/~jdooley/macro/macrohyp/eulerap/eulap.htm

Development of a Tornado Simulator for Assessment of Fluid-Structure Interaction
http://www.osci.ttu.edu/ME_Dept/Faculty/James/tornado.htm

Dynamics of Cloud Street Formation
http://www.met.nps.navy.mil/~durkee/MR3421/Answers/McBride/Q5mBM.htm

Fluid Mechanics Demonstrations
http://www.physics.isu.edu/physdemos/fluids.html

Hands-on Exhibits at INSPIRE
http://science-project.org/inspire/in_exhib.htm

SCI Institute/Research
http://www.sci.utah.edu/research/vr/index.html

The Science of Sound and Music—PHYS-013, Fall 2000
http://www.physics.georgetown.edu/~vincenz/ssm/29/ssm-Lect29.html

Smoke Rings
http://www.nws.noaa.gov/om/educ/activit/smokring.htm

The Tornado Database
http://www.mysteries-megasite.com/main/bigsearch/tornado-3.html

The Tornado Exhibit
http://www.airseds.com/tornado.html

Vortices
http://www.eng.vt.edu/fluids/msc/gallery/vortex/vortex.htm