

### **UNIT CONVERSION - Inches of Water to PSF**

PURPOSE: To Illustrate to the student the procedure for converting Inches Of Water to PSF and canceling units.

- 1) Often times in the study of aeronautics conversion tables or conversion factors are used to convert a reading taken from the instrumentation into another unit. This is required to keep all units the same in the equation
  
- 2) For example a reading in Inches of water must be converted to pounds per square foot (PSF) . (pounds abbreviated = lbs)
  
- 3) This is accomplished by multiplying the inches of water by 0.036128 ( 14.7 PSI / 406.88 Inches of water). To convert lbs per square inch to lbs per square foot multiply inches by 144 (number of square inches in one square foot)
  
- 4) Due to the fact units are being used in all the equations the process for canceling the units becomes very important.

PROPERTIES OF AIR/VELOCITY

EXAMPLE: The units inches of water will cancel leaving the result in PSI (pounds per square inch)

$$25 \text{ inches H}_2\text{O} \times \frac{14.7 \text{ PSI}}{406.88 \text{ inches H}_2\text{O}}$$

$$\frac{\cancel{25 \text{ inches H}_2\text{O}}}{1} \times \frac{14.7 \text{ PSI}}{406.88 \cancel{\text{ inches H}_2\text{O}}}$$

RESULT:  $14.7 / 406.88 = \underline{0.036128} \times 25 = 0.90321 \text{ PSI}$

**0.036128** IS THE CONVERSION FACTOR TO CONVERT INCHES OF WATER TO POUNDS PER SQUARE INCH

## LESSON PLAN VENTURI INSERT

Recommend as prerequisites:

Lesson Plan:	Unit Conversion
Lesson Plan:	Properties of Air
Lesson Plan	Air Velocity Measurement

Lesson Plan: Venturi Insert is divided into 3 progressive levels:

### **Level I**

- Students are provided the area rule formula.
- Students practice solving the formula for area and velocity.
- Using venturi insert A students calculate areas and predict velocities.
- Students compare their predictions to actual velocities measured in the wind tunnel.
- A lab report is written reporting the findings.

### **Level II**

- Students are provided the Bernuolli formula.
- Using venturi insert A students calculate areas, predict pressures, and velocities.
- Students compare their predictions to actual pressure and velocities measured in the wind tunnel.
- A lab report is written reporting the findings.

### **Level III**

- Students are introduced to the concept of flow separation and backflow.
- Students are provided a venturi design criteria chart.
- Venturi B geometry is provided to the students for them to measure. (Venturi B is poorly designed by intent)
- Students are asked to predict the performance of Venturi B.
- Students compare their predictions to actual pressure and velocities measured in the wind tunnel.
- A lab report is written reporting the findings.

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level I**

**Title: Law of Continuity**

**Introduction:** The continuity equation can be used to explain why the flow of a fluid (or air) will change velocity due to the shape of an object.

**Lesson:**

- 1) In aeronautics the shape of an airfoil will create lift. This is accomplished by increasing the velocity of air over the airfoil.
- 2) This velocity change because of the shape is due to the “Law of Continuity.” This law states **Density x Area x Velocity = Constant**
- 3) At velocities less than the speed of sound (subsonic) density will not vary. Density can be deleted and the formula can be simplified to  
**AREA x VELOCITY = CONSTANT**
- 4) As fluid flows through a tube and the area (cross section) of the tube changes the velocity of the fluid will change in relation to the area.
- 5) At low speeds air will have the same properties as a fluid therefore water or fluids can be used to demonstrate these principles.

**Examples:**

- 1) Water flowing in a river. Ask your students what they think will happen to the speed (velocity) of water flowing in a river as the river banks get narrower. (Area of the river is decreased)
- 2) Water flowing over a rock
- 3) Air flowing through an hour glass shaped object (Venturi)
- 4) Ask students to think of other examples of objects that effect the speed of air or water

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level I**

**TITLE: Continuity Math Worksheet**

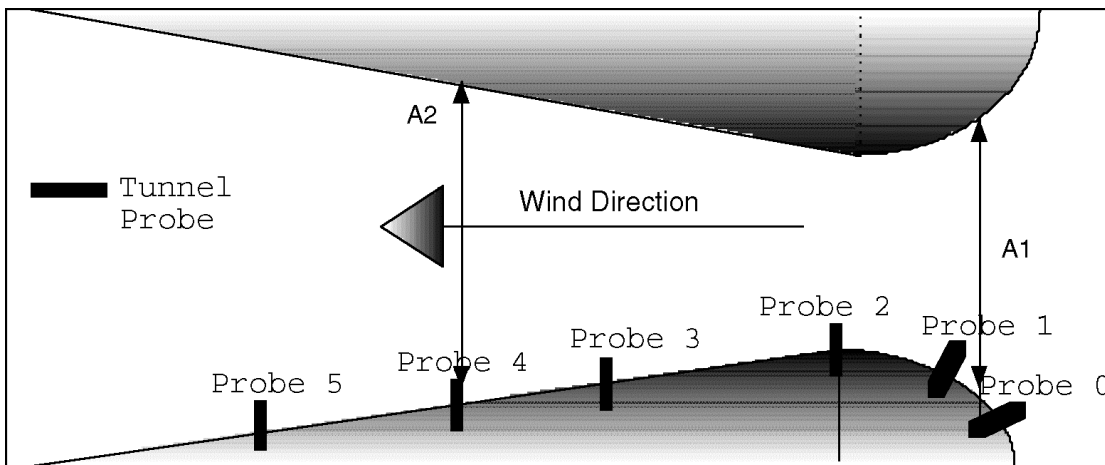
**Introduction:** The following problems are designed to use with the wind tunnel to verify the answers. The data was collected using a venturi in the test section.

**Problems:** Use the formula  $V_1 \times A_1 = V_2 \times A_2$  to solve for the following:

Change the formula to:

$$V_2 = V_1 \times \frac{A_1}{A_2}$$

$V_1 = 50 \text{ mph}$   
 $A_1 = 23.4$   
 $A_2 = 29.4$



**LESSON PLAN I**  
**VENTURI INSERT**  
**Level I**

**Area Rule Practice:**

All answers should be in standard units.

(1) Compute the Velocity ( $V_2$ ) at location 2 for the following problems:

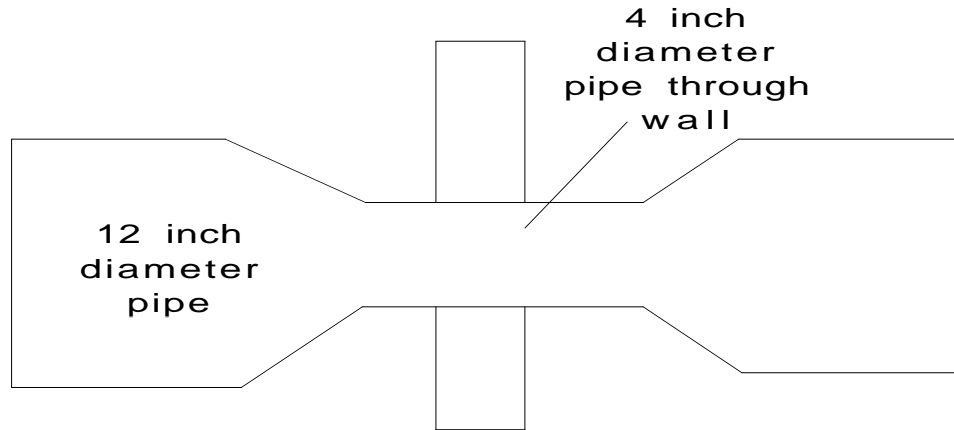
(a)  $A_1 = 5 \text{ ft}^2$        $V_1 = 50 \text{ ft/sec}$        $A_2 = 10 \text{ ft}^2$

(b)  $A_1 = 20 \text{ ft}^2$        $V_1 = 5 \text{ ft/sec}$        $A_2 = 10 \text{ ft}^2$

(c)  $A_1 = 2 \text{ ft}^2$        $V_1 = 4 \text{ miles/hr}$        $A_2 = 1 \text{ ft}^2$

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level I**

- (2) A 12 inch diameter pipe carries water at a velocity of  $15 \text{ ft/sec}$ . The pipe must be reduced to 4 inch diameter to fit through a wall. What will the velocity of the water be in the section that fits through the wall?



- 3) Brainstorming Activity: Have students think of other places where they have seen the shape of an object change the speed of air or water.

Write there applications below:

## **Laboratory Experiment:**

### **Title: Venturi Insert Activities**

**Objective:** To obtain a reading from the wind tunnel test section venturi A and use this readings to calculate the velocity at a second point.

**Safety:** Before Operating the Wind Tunnel perform operational run sheet instructions.

**Tools and equipment:** Venturi (A) test section Inserts, 2 Dwyer water manometers, 10 tube water manometer and tygon tubing.

### **Procedure:**

- 1) Remove second countersunk screws and nuts from the front of the test section ( both sides top and bottom)
- 2) Connect correct tygon numbered tubes to the lower venturi (numbers go at the opposite end from venturi).
- 3) Install the upper venturi A section centered in the top of the test section using long wood screws (place washer under screws).
- 4) Feed the 10 tygon tubes from the lower section through the hole in the center of the test section. As the venturi is brought into place continue pulling tubes (be careful not to disconnect tubes).
- 5) Once the venturi is centered in the lower test section Install the short wood screws to secure venturi.
- 6) To aid the airflow tape the leading edge of the venturi sections to the tunnel floor.
- 7) Connect the numbered tubes to the 10 tube water manometer.
- 8) Run the wind tunnel and confirm the level of the water in the tubes agrees with the shape of the venturi. If not check for leaks.
- 9) Using tee fitting connect Dwyer water manometer to the #3 and #8 static ports.
- 10) Run the wind tunnel and adjust velocity reading from #3 to 45 MPH.

11) Measure the distance from the two venturi sections at #3 and #8 static ports. Lines are on the upper test section opposite of the lower ports.

12) Calculate the Area at #3 and #8 ports:

Remember Area = Length x Width

Test section width = 6.0" if the distance at #3 = 3.9" Area = 6.0" X 3.9"

13) Complete Continuity Math formula to solve for velocity at #8 probe.

14) Run the wind tunnel and check agreement of your answer. (Your answer should agree within 5% of calculated reading.)

15) Repeat the experiment using different velocities.

16) Complete the Continuity Table

Area calculation table:

Static port #	Tunnel Width	Distance Between Ports	AREA
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

**LESSON PLAN**  
**VENTURI INSERT**  
**Level I**

Prepare a run sheet that converts the desired set point velocity in miles/hr to feet/second to be read on probe #1. Also include columns for theoretical values of the velocity reading at probe #2 in feet per second and in miles per hour. Compare these to the actual velocities measured by running this experiment under the supervision of your instructor.

Write in the actual velocity readings in your run log. Write a lab report discussing your procedure and results.

**EXPERIMENT #1 Proof of Area Rule**

Date of Experiment:

Purpose:

Team Members:

**LESSON PLAN**  
**VENTURI INSERT**  
**Level II**

**Teacher's Notes**

**Title: Air Velocity Measurement Calculation**

**Introduction:** Velocity ( speed of the air ) is obtained from reading the air pressure.

**Lesson:**

- 1) To perform aeronautical calculations we must be able to measure the velocity of the air. One of the more accurate means to accomplish this is to use Bernoulli's equation:

**As the velocity increases - pressure decreases**

- 2) By using a pressure reading in Inches of Water (pressure) we are able to calculate the velocity of the air.
- 3) Several steps must be taken to modify Bernoulli's equation for the purpose we need.

$$P_T = P_S + \frac{1}{2} \rho v^2$$

VELOCITY must be moved to the left side of the equation

$$P_T - P_S = \frac{1}{2} \rho v^2$$

To solve for  $\Delta P$  Subtract the Wind Tunnel Total pressure  
From the static pressure reading

$$\Delta P = \frac{1}{2} \rho v^2$$

$$2 \Delta P = \rho v^2$$

To simplify ROH  $\rho$  Multiply  $\Delta P \times 2$

To move ROH to the left side of the equation

$$\frac{2 \Delta P}{\rho} = v^2$$

To solve for velocity squared take the square root of the left side

$$\sqrt{\frac{2 \Delta P}{\rho}} = v$$

We are now able to solve for velocity by taking the square root of  $\Delta P \times 2$  divided by 0.002378

Given the following static pressure readings solve for velocity remember the pressure readings are in inches of water and must first be converted to PSF  
(Inches of water  $\times 0.036128 \times 144$ )

NOTE: For our purposes tunnel pressure is considered to be 0

To convert feet per second to miles per hour (mph) multiply by 0.6818

SAMPLE PROBLEM:

1) Convert (-4.07) in. H<sub>2</sub>O to Velocity

Step 1)  $\Delta P = (-4.07) - 0 = 4.07$  in. H<sub>2</sub>O

Step 2)  $4.07 \times 0.036128 = 0.147$  PSI  $\times 144 = 21.17$  PSF

Step 3)  $2 \times \Delta P = 42.348$

Step 4)  $42.348 / 0.002378 = 17,808.242$

Step 5) sq root of 17,808.242 = 133.44 feet per second(fps)

Step 6)  $133.44 \times .6818 = 90.98$  mph

Answer: 91 mph

**VENTURI INSERT**  
**Level II**

**BERNOULLI FORMULA PRACTICE**

All answers should be in standard units.

- (1) Compute the pressure related to a velocity of:
- (a) 100 ft/sec<sup>2</sup>
  - (b) 100 miles/hr
- (2) What velocity exists if the following pressure is measured?
- (a) 75 lb/ft<sup>2</sup>
  - (b) 0.25 lb/in<sup>2</sup>
  - (c) 5 in H<sub>2</sub>O
- (3) At the entrance to a tunnel test section the area is 2 ft<sup>2</sup>.  
The pressure is measured to be 1 in H<sub>2</sub>O. Compute the pressure at the exit of the test section where the area is 2 ft<sup>2</sup>.

## **Laboratory Experiment Level II**

Title: Air Velocity Calculation

**Objective:** The student will be able to calculate the air velocity in the wind tunnel using the Bernoulli formula. Set up a spreadsheet to enter the data and formula for velocity

**Safety:** Before operating the wind tunnel perform operational run sheet

**Tools and Equipment:** Venturi A test section insert, 2 Dwyer water manometers, 10 tube water manometer and tygon tubing

**Procedure:**

- 1) Remove second countersunk screws and nuts from the front of the test section ( both sides top and bottom)
- 2) Connect correct tygon numbered tubes to the lower venturi (numbers go at the opposite end from venturi).
- 3) Install the upper venturi A section centered in the top of the test section using long wood screws (place washer under screws).
- 4) Feed the 10 tygon tubes from the lower section through the hole in the center of the test section. As the venturi is brought into place continue pulling tubes (be careful not to disconnect tubes).
- 5) Once the venturi is centered in the lower test section Install the short wood screws to secure venturi.
- 6) To aid the airflow tape the leading edge of the venturi sections to the tunnel floor.
- 7) Connect the numbered tubes to the 10 tube water manometer.
- 8) Run the wind tunnel and confirm the level of the water in the tubes agrees with the shape of the venturi. If not check for leaks.
- 9) Using tee fitting connect Dwyer water manometer to the #3 and #8 static ports.
- 10) Run the wind tunnel and adjust velocity reading from #3 to 1" Water
- 11) Calculate the velocity in MPH and FPS solve for velocity at probe #8 and determine the correct reading in Inches of Water.
- 12) Repeat this experiment at several tunnel velocities (at least 3). Create a

spreadsheet in column format that computes the predicted pressures and velocities from the area you measured. The second section of the spreadsheet should calculate the velocity from the measured pressure. Make a column that computes the difference between the measured and predicted velocity. This is the absolute error. In the final column, divide the absolute error by the predicted velocity. This is called the relative error. Your relative error should be less than +/- 5%.

- 13) Write a lab report discussing your procedure and results. You should discuss the accuracy of your results. In particular, discuss the difference between predicted, calculated, and measured values. Which is the correct result?

Date of Experiment:

Purpose:

Team Members:

DESIRED TUNNEL VELOCITY:

ACTUAL TUNNEL VELOCITY:

TAP #	AREA	PREDICTED VELOCITY	PREDICTED PRESSURE	MEASURED PRESSURE	CALCULATED VELOCITY
1					
2					
3					
4					
5					
6					
7					

Observations:

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level III**

**Teacher's Notes:**

The 3rd level incorporates advanced critical thinking and analysis. Students will be given engineering diagram charts to interpret. These charts are not based on exact formulas. A second venturi insert is provided which violates the design charts. Students should be able to use the charts to predict the poor performance. They should be recognize the scientific principle that explains the difference between data obtained and the calculated data.

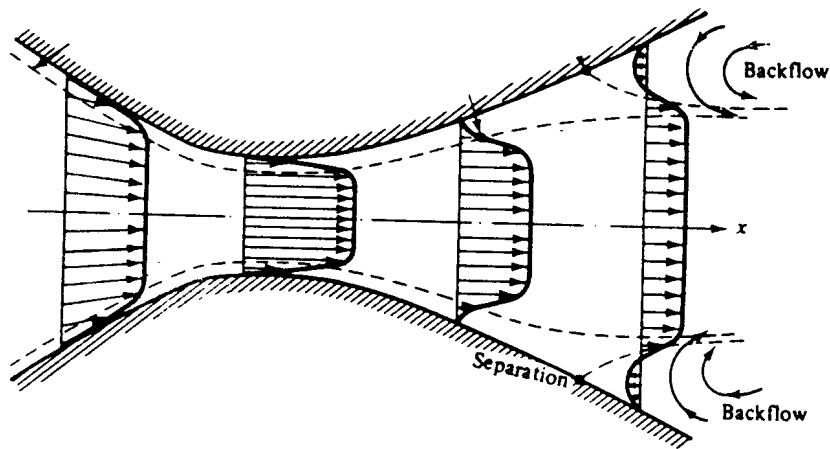
A venturi has a design limitation based on the geometric angle of divergence. The area of the tunnel or venturi decreases from the entrance to the throat of the venturi. The throat of the venturi is the minimum area. After that point, the flow area will increase. As an exercise in Level III you will have the students plot the pressure using knowledge from Levels I & II (area rule and Bernoulli's equation) versus distance in the venturi from entrance to exit. They should note that will from the entrance to the throat the pressure decrease as the area decreases. Then after the throat the area increases so the pressure will decrease.

Ask the students if they think there will be any difference in the flow quality before and after the throat. (There will be.) Air flow naturally wants to move from high pressure to low pressure (give an example of letting air out of a balloon). The students should see that the pressure in the venturi does move from high pressure to low pressure in the entrance. But after the throat the flow is going from low to high pressure. This is unnatural and will only occur when air is forced. Students should recognize that it is possible something different should happen.

Refer to figure 1. In the inlet, since the air is being compressed (low to high pressure) it can easily follow converging (or decreasing area) wall angles. It can do so up to  $45^\circ$ . Show the venturi or venturi drawing to the students to illustrate this. However, since the flow does not move from the low pressure to high pressure as well, it can not follow the wall diverging (increasing area) angle. If this angle is too great, the flow will separate. (this provides an insight to stall in the next lesson plan) This means that there is an area near the wall where the velocity is near zero. In extreme cases, flow in the opposite direction may occur (backflow). In practice what this means is the equations are no longer accurate if you exceed a divergence angle of  $10^\circ$ .

Venturi B does have a divergence angle of greater than  $10^\circ$  and the data will not agree with predictions. The error increases with velocity and area. This concept of a difference between assumptions and measurements is referred to in the Proficiency Test.

The Venturi Design Chart provides the design criteria.



converging section

area decreases  
favorable pressure change  
good flow

diverging section

area increases  
unfavorable pressure change  
poor flow

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level III**

**PRESSURE PROFILE WORKSHEET**

Using the chart provided compute the pressure through the venturi from the inlet through the throat and from the throat to the exit. The locations of the pressure taps are provided. The pressure at these locations should be plotted plus a point halfway in between each tap. Do this for each venturi on the graph provided.

Discuss with the class and your teacher your results.

Is there a difference in the pressure before and after the venturi throat?

The chart provided is a venturi design chart. If a venturi is well designed it should perform well. Good performance is defined if the actual pressure and velocity readings agree with the calculated values. If a venturi is poorly designed the measured values will not agree with the calculated.

The chart requires that you measure the certain dimensions on the venturi. Do this on the worksheet provided.

VENTURI	Length, L	Width, W	Angle, $\Theta$	2 x $\Theta$	Stall?
A					
B					

According to the venturi design chart which venturi is a better design?

**LESSON PLAN I**  
**AIRFOIL SECTION**  
**Level I**

**AIRFOIL TERMINOLOGY**

The following terms will be used in this lesson plan:

Leading Edge - The front of the airfoil (tip).

Trailing Edge - The aft (rear) edge of the airfoil.

Chord or Chordline - An imaginary straight line which passes through an airfoil or wing section from the leading to trailing edge.

Chord Length - Distance between the leading and trailing edges of an airfoil.

Angle of Attack - The angle formed between the wind striking an airfoil and the chordline of the airfoil.

Camberline (meanline) - a line connecting all points midway between the upper and lower surfaces of the airfoil.

Camber - A perpendicular distance between the shoreline and the camberline.

Symmetrical Airfoil - A airfoil that has the same shape on both sides of its centerline.

Asymmetrical Airfoil - A airfoil that has a different upper shape than lower shape. (cambered airfoil).

Wing Span - The length of an aircraft wing (when the aircraft is viewed head-on).

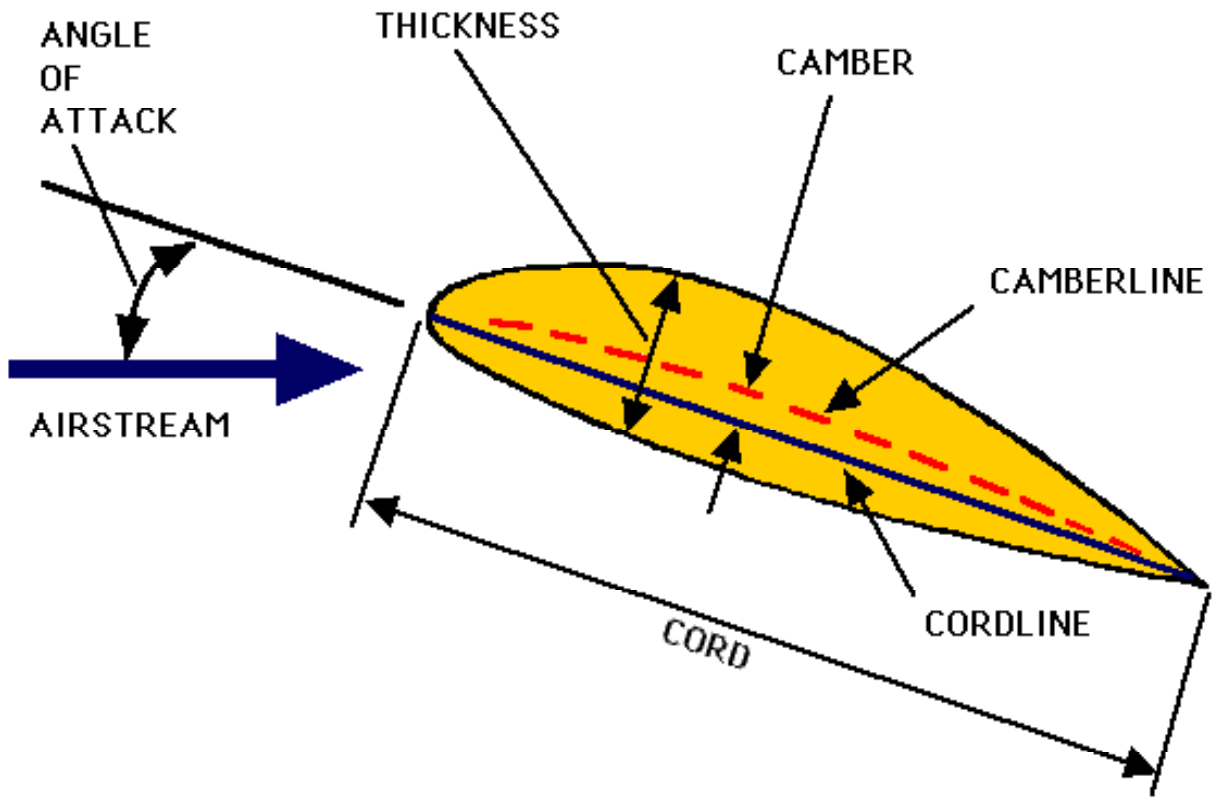
Delta  $\Delta$  - Difference between static and dynamic pressure ( $\Delta P$ ).

Roh  $\rho$  - air density at standard day (0.02378 slugs per cubic foot).

Alpha  $\alpha$  - angle of attack in degrees.

Coefficient - A dimensionless number used to express magnitude.

**LESSON PLAN I**  
**AIRFOIL SECTION**  
**Level I**



**AIRFOIL GEOMETRY**

**LESSON PLAN I**  
**AIRFOIL SECTION**  
**Level I**

**SCALING LAW**

Geometric Similarity is the engineering term used to describe the rules that allow a scale model of an aerodynamic object to be tested. Usually, due to limited space, an object is scaled down. An example is a 1/32nd scale hobby-model aircraft. Engineers use scale models to test various designs and learn about basic theory.

Each dimension of the object should be scaled in order to be geometrically similar. In the above example, the length, height, and width would be multiplied by 1/32. An F-16 aircraft that has a wing span of 31 ft., a length of 47 ft., 8 in., and a height of 16 ft. 5 in. The wing area is 33.34 *square* feet. At this scale, the model would have a wing span of 11<sup>5</sup>/<sub>8</sub> in., a length of 1 ft., 5<sup>7</sup>/<sub>8</sub> in., and a height of 6<sup>1</sup>/<sub>8</sub> in. The wing area would be 4<sup>5</sup>/<sub>8</sub> *square* inches. Note that since area has two dimensions, the full scale number was divided by (1/32) *squared*.

In order to isolate the primary force, sometimes only one dimension is scaled. An example is the difference between scaling a wing (area) and an airfoil (length). Since the airfoil shape is usually constant at any point along the span of the wing, the airflow characteristics or pressure over the wing section will be the same all along the wing span. The primary force due to the pressure doesn't change along the *wing span*. However, as will be seen in the experiments, the pressure changes dramatically along the *chord*. This is why the wing is scaled in only one direction - the chord. This deliberate scaling in only one direction is called the *characteristic* dimension.

There are some differences due end effects. End effects are from the fuselage and the wing tip can also be tested. This generally has small effects on lift.

The airfoil *characteristic* dimension is the chord length, *c* (see figure). The ratio between the chord length of the tunnel model airfoil and the prototype airfoil is the scale of the model. The chord lengths must be in the same units so that the scale will be dimensionless.

When the geometric similarity occurs, the primary forces on the object will also be scaled. For the airfoil example, the primary force is lift. Therefore if a 1/10th scale airfoil is tested in a wind tunnel, the lift measured will be 1/10th of the lift on the full-scale airfoil. To obtain the lift expected on the full-scale airfoil, multiply by 10.

In order to minimize the effect of scaling on the answer, and also to eliminate confusion over whether English or SI units are chosen, aerodynamic forces are expressed in dimensionless *coefficient* form. The actual physical parameter (force or pressure) is divided by a combination of geometric and flow conditions. The specific combination of parameters has generally been identified in advance from historical research.

If the non-dimensionalizing parameter has been properly chosen, it will cause data taken at many different conditions to collapse to a single line, thus eliminating the need to take data at each and every condition.

(Incidentally, identification of non-dimensional parameters by a researcher is a worthy achievement. It usually signifies an new understanding of a phenomenon and leads to engineering development).

The first dimensionless coefficients used in this lesson plan is the pressure coefficient. The pressure coefficient (sometimes called the coefficient of pressure) is defined as:

$$C_p = \frac{P_s - P_\infty}{\frac{1}{2}(\rho / g_0)V_0^2}$$

Where the following symbols are defined as:

- $C_p$  = Pressure Coefficient (dimensionless).
- $P_s$  = Pressure in physical units on airfoil surface ( $\text{lb}/\text{ft}^2$ ).
- $P_\infty$  = Pressure in physical units at infinity ( $\text{lb}/\text{ft}^2$ ).
- $\rho$  = Density ( $0.0767 \text{ lb}/\text{ft}^3$ ).
- $g_0$  = Gravitational constant ( $32.2 \text{ ft}/\text{sec}^2$ ).
- $V_0$  = Tunnel Velocity ( $\text{ft}/\text{sec}$ ).

As you can see the units cancel:  $[(\text{lb}/\text{ft}^2)(\text{ft}/\text{sec}^2)]/[(\text{lb}/\text{ft}^3)(\text{ft}/\text{sec})^2]$ .

The quantity in the denominator is called the dynamic pressure, q. It has units of pressure and is the pressure caused by velocity.

$$C_p = \frac{P_s - P_\infty}{q}$$

This formula can be manipulated when taking data in the wind tunnel, using the following physical interpretation (since the reading is often referenced to the atmospheric pressure):

$$P_s = P_{\text{reading}} + P_{\text{atm}} \quad \text{and} \quad P_\infty = P_{\text{tunnel static}}$$

$$P_s - P_\infty = P_{\text{reading}} + P_{\text{atm}} - P_{\text{tunnel static}}$$

If there are no losses in the tunnel, the total pressure is equal to the atmospheric pressure.

$$P_s - P_\infty = P_{\text{reading}} + P_{\text{total}} - P_{\text{tunnel static}}$$

The dynamic pressure was defined earlier as the difference between the total and static pressures. (See the general and Venturi lesson plans).

$$\begin{aligned}P_{\text{total}} &= P_{\text{tunnel static}} + P_{\text{dynamic}} \\P_{\text{total}} &= P_{\text{tunnel static}} + q\end{aligned}$$

re-arranging;

$$P_{\text{total}} - P_{\text{tunnel static}} = q$$

$$P_s - P_\infty = P_{\text{reading}} + (P_{\text{total}} - P_{\text{tunnel static}}) = P_{\text{reading}} + q$$

So finally, the wind tunnel format for pressure coefficient is:

$$C_p = \frac{P_{rdg} + q}{q} = \frac{P_{rdg}}{q} + 1$$

## PROPERTIES OF AIR/VELOCITY

### **UNIT CONVERSION - Inches of Water to PSF**

PURPOSE: To Illustrate to the student the procedure for converting Inches Of Water to PSF and canceling units.

- 2) Often times in the study of aeronautics conversion tables or conversion factors are used to convert a reading taken from the instrumentation into another unit. This is required to keep all units the same in the equation
- 3) For example a reading in Inches of water must be converted to pounds per square foot (PSF) . (pounds abbreviated = lbs)
- 4) This is accomplished by multiplying the inches of water by 0.036128 ( 14.7 PSI / 406.88 Inches of water). To convert lbs per square inch to lbs per square foot multiply inches by 144 (number of square inches in one square foot)
- 5) Due to the fact units are being used in all the equations the process for canceling the units becomes very important.

PROPERTIES OF AIR/VELOCITY

EXAMPLE: The units inches of water will cancel leaving the result in PSI (pounds per square inch)

$$25 \text{ inches H}_2\text{O} \times \frac{14.7 \text{ PSI}}{406.88 \text{ inches H}_2\text{O}}$$

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RESULT:  $14.7 / 406.88 = \underline{0.036128} \times 25 = 0.90321 \text{ PSI}$

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## LESSON PLAN VENTURI INSERT

Recommend as prerequisites:

Lesson Plan:	Unit Conversion
Lesson Plan:	Properties of Air
Lesson Plan	Air Velocity Measurement

Lesson Plan: Venturi Insert is divided into 3 progressive levels:

### **Level I**

- Students are provided the area rule formula.
- Students practice solving the formula for area and velocity.
- Using venturi insert A students calculate areas and predict velocities.
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- A lab report is written reporting the findings.

### **Level II**

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- Students compare their predictions to actual pressure and velocities measured in the wind tunnel.
- A lab report is written reporting the findings.

### **Level III**

- Students are introduced to the concept of flow separation and backflow.
- Students are provided a venturi design criteria chart.
- Venturi B geometry is provided to the students for them to measure. (Venturi B is poorly designed by intent)
- Students are asked to predict the performance of Venturi B.
- Students compare their predictions to actual pressure and velocities measured in the wind tunnel.
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**LESSON PLAN I**  
**VENTURI INSERT**  
**Level I**

**Title: Law of Continuity**

**Introduction:** The continuity equation can be used to explain why the flow of a fluid (or air) will change velocity due to the shape of an object.

**Lesson:**

- 2) In aeronautics the shape of an airfoil will create lift. This is accomplished by increasing the velocity of air over the airfoil.
- 3) This velocity change because of the shape is due to the “Law of Continuity.” This law states **Density x Area x Velocity = Constant**
- 4) At velocities less than the speed of sound (subsonic) density will not vary. Density can be deleted and the formula can be simplified to  
**AREA x VELOCITY = CONSTANT**
- 5) As fluid flows through a tube and the area (cross section) of the tube changes the velocity of the fluid will change in relation to the area.
- 6) At low speeds air will have the same properties as a fluid therefore water or fluids can be used to demonstrate these principles.

**Examples:**

- 2) Water flowing in a river. Ask your students what they think will happen to the speed (velocity) of water flowing in a river as the river banks get narrower. (Area of the river is decreased)
- 3) Water flowing over a rock
- 4) Air flowing threw an hour glass shaped object (Venturi)
- 5) Ask students to think of other examples of objects that effect the speed of air or water

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level I**

**TITLE: Continuity Math Worksheet**

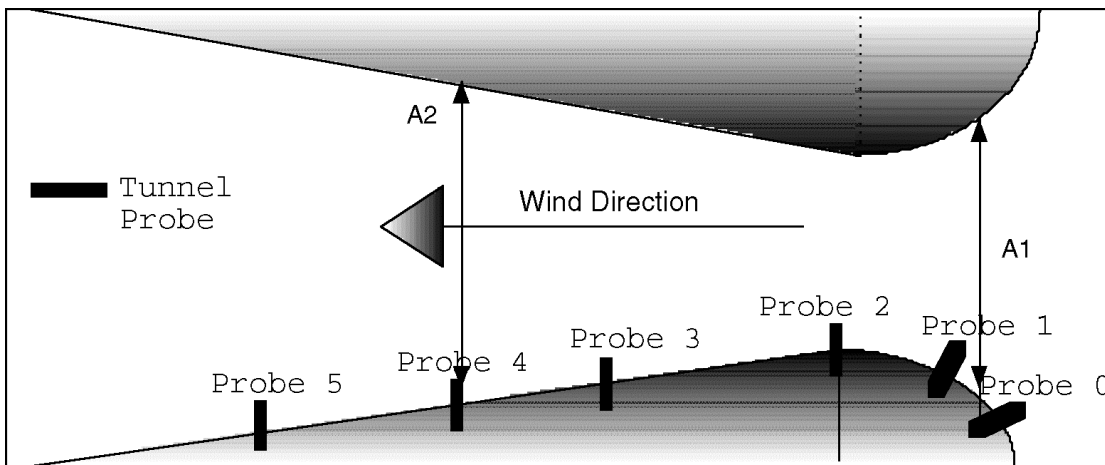
**Introduction:** The following problems are designed to use with the wind tunnel to verify the answers. The data was collected using a venturi in the test section.

**Problems:** Use the formula  $V_1 \times A_1 = V_2 \times A_2$  to solve for the following:

Change the formula to:

$$V_2 = V_1 \times \frac{A_1}{A_2}$$

$V_1 = 50 \text{ mph}$   
 $A_1 = 23.4$   
 $A_2 = 29.4$



**LESSON PLAN I**  
**VENTURI INSERT**  
**Level I**

**Area Rule Practice:**

All answers should be in standard units.

(1) Compute the Velocity ( $V_2$ ) at location 2 for the following problems:

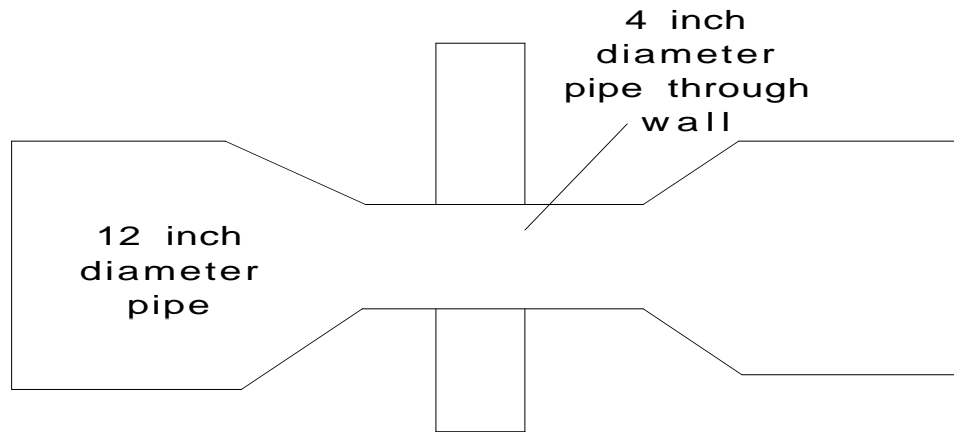
(a)  $A_1 = 5 \text{ ft}^2$        $V_1 = 50 \text{ ft/sec}$        $A_2 = 10 \text{ ft}^2$

(b)  $A_1 = 20 \text{ ft}^2$        $V_1 = 5 \text{ ft/sec}$        $A_2 = 10 \text{ ft}^2$

(d)  $A_1 = 2 \text{ ft}^2$        $V_1 = 4 \text{ miles/hr}$        $A_2 = 1 \text{ ft}^2$

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level I**

- (2) A 12 inch diameter pipe carries water at a velocity of  $15 \text{ ft/sec}$ . The pipe must be reduced to 4 inch diameter to fit through a wall. What will the velocity of the water be in the section that fits through the wall?



- 4) Brainstorming Activity: Have students think of other places where they have seen the shape of an object change the speed of air or water.

Write there applications below:

## **Laboratory Experiment:**

### **Title: Venturi Insert Activities**

**Objective:** To obtain a reading from the wind tunnel test section venturi A and use this readings to calculate the velocity at a second point.

**Safety:** Before Operating the Wind Tunnel perform operational run sheet instructions.

**Tools and equipment:** Venturi (A) test section Inserts, 2 Dwyer water manometers, 10 tube water manometer and tygon tubing.

### **Procedure:**

- 3) Remove second countersunk screws and nuts from the front of the test section ( both sides top and bottom)
- 4) Connect correct tygon numbered tubes to the lower venturi (numbers go at the opposite end from venturi).
- 17) Install the upper venturi A section centered in the top of the test section using long wood screws (place washer under screws).
- 18) Feed the 10 tygon tubes from the lower section through the hole in the center of the test section. As the venturi is brought into place continue pulling tubes (be careful not to disconnect tubes).
- 19) Once the venturi is centered in the lower test section Install the short wood screws to secure venturi.
- 20) To aid the airflow tape the leading edge of the venturi sections to the tunnel floor.
- 21) Connect the numbered tubes to the 10 tube water manometer.
- 22) Run the wind tunnel and confirm the level of the water in the tubes agrees with the shape of the venturi. If not check for leaks.
- 23) Using tee fitting connect Dwyer water manometer to the #3 and #8 static ports.
- 24) Run the wind tunnel and adjust velocity reading from #3 to 45 MPH.

25) Measure the distance from the two venturi sections at #3 and #8 static ports. Lines are on the upper test section opposite of the lower ports.

26) Calculate the Area at #3 and #8 ports:

Remember Area = Length x Width

Test section width = 6.0" if the distance at #3 = 3.9" Area = 6.0" X 3.9"

27) Complete Continuity Math formula to solve for velocity at #8 probe.

28) Run the wind tunnel and check agreement of your answer. (Your answer should agree within 5% of calculated reading.)

29) Repeat the experiment using different velocities.

30) Complete the Continuity Table

Area calculation table:

Static port #	Tunnel Width	Distance Between Ports	AREA
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

**LESSON PLAN**  
**VENTURI INSERT**  
**Level I**

Prepare a run sheet that converts the desired set point velocity in miles/hr to feet/second to be read on probe #1. Also include columns for theoretical values of the velocity reading at probe #2 in feet per second and in miles per hour. Compare these to the actual velocities measured by running this experiment under the supervision of your instructor.

Write in the actual velocity readings in your run log. Write a lab report discussing your procedure and results.

**EXPERIMENT #1 Proof of Area Rule**

Date of Experiment:

Purpose:

Team Members:

**LESSON PLAN**  
**VENTURI INSERT**  
**Level II**

**Teacher's Notes**

**Title: Air Velocity Measurement Calculation**

**Introduction:** Velocity ( speed of the air ) is obtained from reading the air pressure.

**Lesson:**

- 2) To perform aeronautical calculations we must be able to measure the velocity of the air. One of the more accurate means to accomplish this is to use Bernoulli's equation:

**As the velocity increases - pressure decreases**

- 3) By using a pressure reading in Inches of Water (pressure) we are able to calculate the velocity of the air.
- 4) Several steps must be taken to modify Bernoulli's equation for the purpose we need.

$$P_T = P_S + \frac{1}{2} \rho v^2$$

VELOCITY must be moved to the left side of the equation

$$P_T - P_S = \frac{1}{2} \rho v^2$$

To solve for  $\Delta P$  Subtract the Wind Tunnel Total pressure  
From the static pressure reading

$$\Delta P = \frac{1}{2} \rho v^2$$

$$2 \Delta P = \rho v^2$$

To simplify ROH  $\rho$  Multiply  $\Delta P \times 2$

To move ROH to the left side of the equation

$$\frac{2 \Delta P}{\rho} = v^2$$

To solve for velocity squared take the square root of the left side

$$\sqrt{\frac{2 \Delta P}{\rho}} = v$$

We are now able to solve for velocity by taking the square root of  $\Delta P \times 2$  divided by 0.002378

Given the following static pressure readings solve for velocity remember the pressure readings are in inches of water and must first be converted to PSF  
(Inches of water  $\times 0.036128 \times 144$ )

NOTE: For our purposes tunnel pressure is considered to be 0

To convert feet per second to miles per hour (mph) multiply by 0.6818

SAMPLE PROBLEM:

1) Convert (-4.07) in. H<sub>2</sub>O to Velocity

Step 1)  $\Delta P = (-4.07) - 0 = 4.07$  in. H<sub>2</sub>O

Step 2)  $4.07 \times 0.036128 = 0.147$  PSI  $\times 144 = 21.17$  PSF

Step 3)  $2 \times \Delta P = 42.348$

Step 4)  $42.348 / 0.002378 = 17,808.242$

Step 5) sq root of 17,808.242 = 133.44 feet per second(fps)

Step 6)  $133.44 \times .6818 = 90.98$  mph

Answer: 91 mph

**VENTURI INSERT**  
**Level II**

**BERNOULLI FORMULA PRACTICE**

All answers should be in standard units.

(1) Compute the pressure related to a velocity of:

(a)  $100 \text{ ft/sec}^2$

(b)  $100 \text{ miles/hr}$

(2) What velocity exists if the following pressure is measured?

(a)  $75 \text{ lb/ft}^2$

(b)  $0.25 \text{ lb/in}^2$

(c)  $5 \text{ in H}_2\text{O}$

(3) At the entrance to a tunnel test section the area is  $2 \text{ ft}^2$ .

The pressure is measured to be  $1 \text{ in H}_2\text{O}$ . Compute the pressure at the exit of the test section where the area is  $2 \text{ ft}^2$ .

## **Laboratory Experiment Level II**

Title: Air Velocity Calculation

**Objective:** The student will be able to calculate the air velocity in the wind tunnel using the Bernoulli formula. Set up a spreadsheet to enter the data and formula for velocity

**Safety:** Before operating the wind tunnel perform operational run sheet

**Tools and Equipment:** Venturi A test section insert, 2 Dwyer water manometers, 10 tube water manometer and tygon tubing

**Procedure:**

- 3) Remove second countersunk screws and nuts from the front of the test section ( both sides top and bottom)
- 4) Connect correct tygon numbered tubes to the lower venturi (numbers go at the opposite end from venturi).
- 14) Install the upper venturi A section centered in the top of the test section using long wood screws (place washer under screws).
- 15) Feed the 10 tygon tubes from the lower section through the hole in the center of the test section. As the venturi is brought into place continue pulling tubes (be careful not to disconnect tubes).
- 16) Once the venturi is centered in the lower test section Install the short wood screws to secure venturi.
- 17) To aid the airflow tape the leading edge of the venturi sections to the tunnel floor.
- 18) Connect the numbered tubes to the 10 tube water manometer.
- 19) Run the wind tunnel and confirm the level of the water in the tubes agrees with the shape of the venturi. If not check for leaks.
- 20) Using tee fitting connect Dwyer water manometer to the #3 and #8 static ports.
- 21) Run the wind tunnel and adjust velocity reading from #3 to 1" Water
- 22) Calculate the velocity in MPH and FPS solve for velocity at probe #8 and determine the correct reading in Inches of Water.
- 23) Repeat this experiment at several tunnel velocities (at least 3). Create a

spreadsheet in column format that computes the predicted pressures and velocities from the area you measured. The second section of the spreadsheet should calculate the velocity from the measured pressure. Make a column that computes the difference between the measured and predicted velocity. This is the absolute error. In the final column, divide the absolute error by the predicted velocity. This is called the relative error. Your relative error should be less than +/- 5%.

- 24) Write a lab report discussing your procedure and results. You should discuss the accuracy of your results. In particular, discuss the difference between predicted, calculated, and measured values. Which is the correct result?

Date of Experiment:

Purpose:

Team Members:

DESIRED TUNNEL VELOCITY:

ACTUAL TUNNEL VELOCITY:

TAP #	AREA	PREDICTED VELOCITY	PREDICTED PRESSURE	MEASURED PRESSURE	CALCULATED VELOCITY
1					
2					
3					
4					
5					
6					
7					

Observations:

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level III**

**Teacher's Notes:**

The 3rd level incorporates advanced critical thinking and analysis. Students will be given engineering diagram charts to interpret. These charts are not based on exact formulas. A second venturi insert is provided which violates the design charts. Students should be able to use the charts to predict the poor performance. They should be recognize the scientific principle that explains the difference between data obtained and the calculated data.

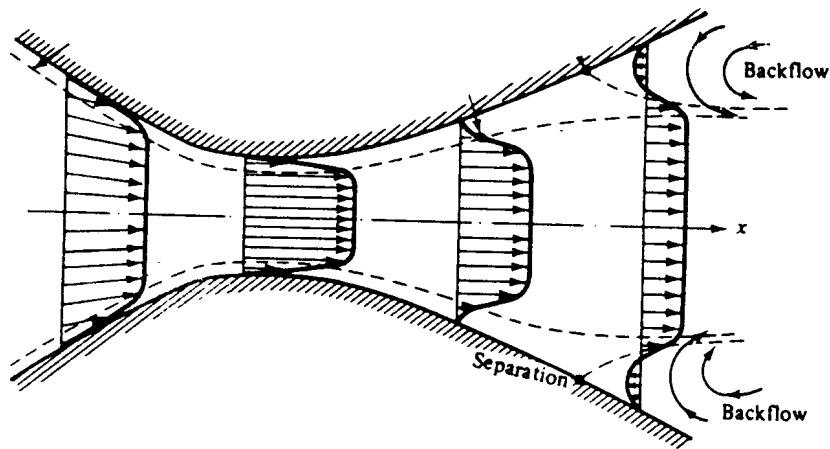
A venturi has a design limitation based on the geometric angle of divergence. The area of the tunnel or venturi decreases from the entrance to the throat of the venturi. The throat of the venturi is the minimum area. After that point, the flow area will increase. As an exercise in Level III you will have the students plot the pressure using knowledge from Levels I & II (area rule and Bernoulli's equation) versus distance in the venturi from entrance to exit. They should note that will from the entrance to the throat the pressure decrease as the area decreases. Then after the throat the area increases so the pressure will decrease.

Ask the students if they think there will be any difference in the flow quality before and after the throat. (There will be.) Air flow naturally wants to move from high pressure to low pressure (give an example of letting air out of a balloon). The students should see that the pressure in the venturi does move from high pressure to low pressure in the entrance. But after the throat the flow is going from low to high pressure. This is unnatural and will only occur when air is forced. Students should recognize that it is possible something different should happen.

Refer to figure 1. In the inlet, since the air is being compressed (low to high pressure) it can easily follow converging (or decreasing area) wall angles. It can do so up to  $45^\circ$ . Show the venturi or venturi drawing to the students to illustrate this. However, since the flow does not move from the low pressure to high pressure as well, it can not follow the wall diverging (increasing area) angle. If this angle is too great, the flow will separate. (this provides an insight to stall in the next lesson plan) This means that there is an area near the wall where the velocity is near zero. In extreme cases, flow in the opposite direction may occur (backflow). In practice what this means is the equations are no longer accurate if you exceed a divergence angle of  $10^\circ$ .

Venturi B does have a divergence angle of greater than  $10^\circ$  and the data will not agree with predictions. The error increases with velocity and area. This concept of a difference between assumptions and measurements is referred to in the Proficiency Test.

The Venturi Design Chart provides the design criteria.



converging section

area decreases  
favorable pressure change  
good flow

diverging section

area increases  
unfavorable pressure change  
poor flow

**LESSON PLAN I**  
**VENTURI INSERT**  
**Level III**

**PRESSURE PROFILE WORKSHEET**

Using the chart provided compute the pressure through the venturi from the inlet through the throat and from the throat to the exit. The locations of the pressure taps are provided. The pressure at these locations should be plotted plus a point halfway in between each tap. Do this for each venturi on the graph provided.

Discuss with the class and your teacher your results.

Is there a difference in the pressure before and after the venturi throat?

The chart provided is a venturi design chart. If a venturi is well designed it should perform well. Good performance is defined if the actual pressure and velocity readings agree with the calculated values. If a venturi is poorly designed the measured values will not agree with the calculated.

The chart requires that you measure the certain dimensions on the venturi. Do this on the worksheet provided.

VENTURI	Length, L	Width, W	Angle, $\Theta$	2 x $\Theta$	Stall?
A					
B					

According to the venturi design chart which venturi is a better design?

**LESSON PLAN I**  
**AIRFOIL SECTION**  
**Level I**

**AIRFOIL TERMINOLOGY**

The following terms will be used in this lesson plan:

Leading Edge - The front of the airfoil (tip).

Trailing Edge - The aft (rear) edge of the airfoil.

Chord or Chordline - An imaginary straight line which passes through an airfoil or wing section from the leading to trailing edge.

Chord Length - Distance between the leading and trailing edges of an airfoil.

Angle of Attack - The angle formed between the wind striking an airfoil and the chordline of the airfoil.

Camberline (meanline) - a line connecting all points midway between the upper and lower surfaces of the airfoil.

Camber - A perpendicular distance between the shoreline and the camberline.

Symmetrical Airfoil - A airfoil that has the same shape on both sides of its centerline.

Asymmetrical Airfoil - A airfoil that has a different upper shape than lower shape. (cambered airfoil).

Wing Span - The length of an aircraft wing (when the aircraft is viewed head-on).

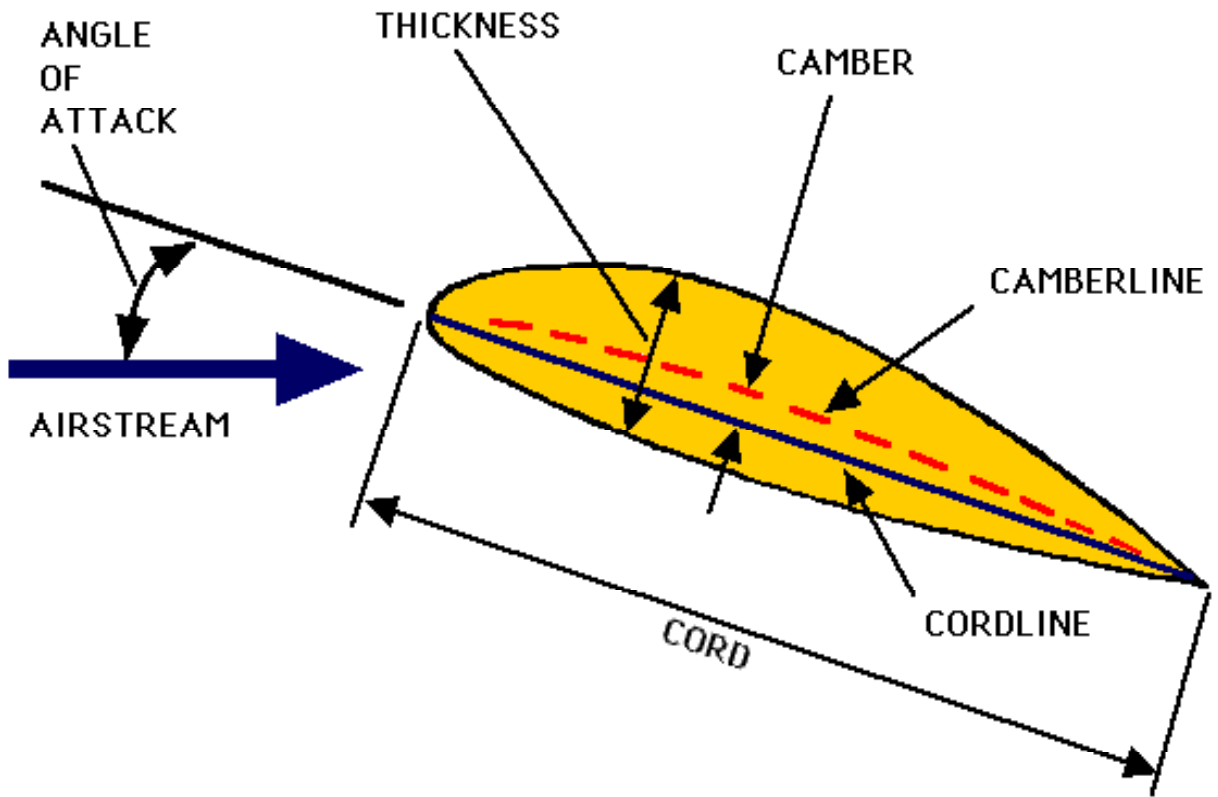
Delta  $\Delta$  - Difference between static and dynamic pressure ( $\Delta P$ ).

Roh  $\rho$  - air density at standard day (0.02378 slugs per cubic foot).

Alpha  $\alpha$  - angle of attack in degrees.

Coefficient - A dimensionless number used to express magnitude.

**LESSON PLAN I**  
**AIRFOIL SECTION**  
**Level I**



**AIRFOIL GEOMETRY**

**LESSON PLAN I**  
**AIRFOIL SECTION**  
**Level I**

**SCALING LAW**

Geometric Similarity is the engineering term used to describe the rules that allow a scale model of an aerodynamic object to be tested. Usually, due to limited space, an object is scaled down. An example is a 1/32nd scale hobby-model aircraft. Engineers use scale models to test various designs and learn about basic theory.

Each dimension of the object should be scaled in order to be geometrically similar. In the above example, the length, height, and width would be multiplied by 1/32. An F-16 aircraft that has a wing span of 31 ft., a length of 47 ft., 8 in., and a height of 16 ft. 5 in. The wing area is 33.34 *square* feet. At this scale, the model would have a wing span of 11<sup>5</sup>/<sub>8</sub> in., a length of 1 ft., 5<sup>7</sup>/<sub>8</sub> in., and a height of 6<sup>1</sup>/<sub>8</sub> in. The wing area would be 4<sup>5</sup>/<sub>8</sub> *square* inches. Note that since area has two dimensions, the full scale number was divided by (1/32) *squared*.

In order to isolate the primary force, sometimes only one dimension is scaled. An example is the difference between scaling a wing (area) and an airfoil (length). Since the airfoil shape is usually constant at any point along the span of the wing, the airflow characteristics or pressure over the wing section will be the same all along the wing span. The primary force due to the pressure doesn't change along the *wing span*. However, as will be seen in the experiments, the pressure changes dramatically along the *chord*. This is why the wing is scaled in only one direction - the chord. This deliberate scaling in only one direction is called the *characteristic* dimension.

There are some differences due end effects. End effects are from the fuselage and the wing tip can also be tested. This generally has small effects on lift.

The airfoil *characteristic* dimension is the chord length, *c* (see figure). The ratio between the chord length of the tunnel model airfoil and the prototype airfoil is the scale of the model. The chord lengths must be in the same units so that the scale will be dimensionless.

When the geometric similarity occurs, the primary forces on the object will also be scaled. For the airfoil example, the primary force is lift. Therefore if a 1/10th scale airfoil is tested in a wind tunnel, the lift measured will be 1/10th of the lift on the full-scale airfoil. To obtain the lift expected on the full-scale airfoil, multiply by 10.

In order to minimize the effect of scaling on the answer, and also to eliminate confusion over whether English or SI units are chosen, aerodynamic forces are expressed in dimensionless *coefficient* form. The actual physical parameter (force or pressure) is divided by a combination of geometric and flow conditions. The specific combination of parameters has generally been identified in advance from historical research.

If the non-dimensionalizing parameter has been properly chosen, it will cause data taken at many different conditions to collapse to a single line, thus eliminating the need to take data at each and every condition.

(Incidentally, identification of non-dimensional parameters by a researcher is a worthy achievement. It usually signifies an new understanding of a phenomenon and leads to engineering development).

The first dimensionless coefficients used in this lesson plan is the pressure coefficient. The pressure coefficient (sometimes called the coefficient of pressure) is defined as:

$$C_p = \frac{P_s - P_\infty}{\frac{1}{2}(\rho / g_0)V_0^2}$$

Where the following symbols are defined as:

- $C_p$  = Pressure Coefficient (dimensionless).
- $P_s$  = Pressure in physical units on airfoil surface ( $\text{lb}/\text{ft}^2$ ).
- $P_\infty$  = Pressure in physical units at infinity ( $\text{lb}/\text{ft}^2$ ).
- $\rho$  = Density ( $0.0767 \text{ lb}/\text{ft}^3$ ).
- $g_0$  = Gravitational constant ( $32.2 \text{ ft}/\text{sec}^2$ ).
- $V_0$  = Tunnel Velocity ( $\text{ft}/\text{sec}$ ).

As you can see the units cancel:  $[(\text{lb}/\text{ft}^2)(\text{ft}/\text{sec}^2)]/[(\text{lb}/\text{ft}^3)(\text{ft}/\text{sec})^2]$ .

The quantity in the denominator is called the dynamic pressure, q. It has units of pressure and is the pressure caused by velocity.

$$C_p = \frac{P_s - P_\infty}{q}$$

This formula can be manipulated when taking data in the wind tunnel, using the following physical interpretation (since the reading is often referenced to the atmospheric pressure):

$$P_s = P_{\text{reading}} + P_{\text{atm}} \quad \text{and} \quad P_\infty = P_{\text{tunnel static}}$$

$$P_s - P_\infty = P_{\text{reading}} + P_{\text{atm}} - P_{\text{tunnel static}}$$

If there are no losses in the tunnel, the total pressure is equal to the atmospheric pressure.

$$P_s - P_\infty = P_{\text{reading}} + P_{\text{total}} - P_{\text{tunnel static}}$$

The dynamic pressure was defined earlier as the difference between the total and static pressures. (See the general and Venturi lesson plans).

$$\begin{aligned}P_{\text{total}} &= P_{\text{tunnel static}} + P_{\text{dynamic}} \\P_{\text{total}} &= P_{\text{tunnel static}} + q\end{aligned}$$

re-arranging;

$$P_{\text{total}} - P_{\text{tunnel static}} = q$$

$$P_s - P_\infty = P_{\text{reading}} + (P_{\text{total}} - P_{\text{tunnel static}}) = P_{\text{reading}} + q$$

So finally, the wind tunnel format for pressure coefficient is:

$$C_p = \frac{P_{rdg} + q}{q} = \frac{P_{rdg}}{q} + 1$$