AC 2008-2117: A SIMPLE EDUCATIONAL WIND TUNNEL SETUP FOR VISUALIZATION OF DUCT FLOW STREAMLINES AND NOZZLE/DIFFUSER BOUNDARY LAYER SEPARATION

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A Simple Educational Wind Tunnel Setup for Visualization of Duct Flow Streamlines and Nozzle/Diffuser Boundary Layer Separation

Abstract

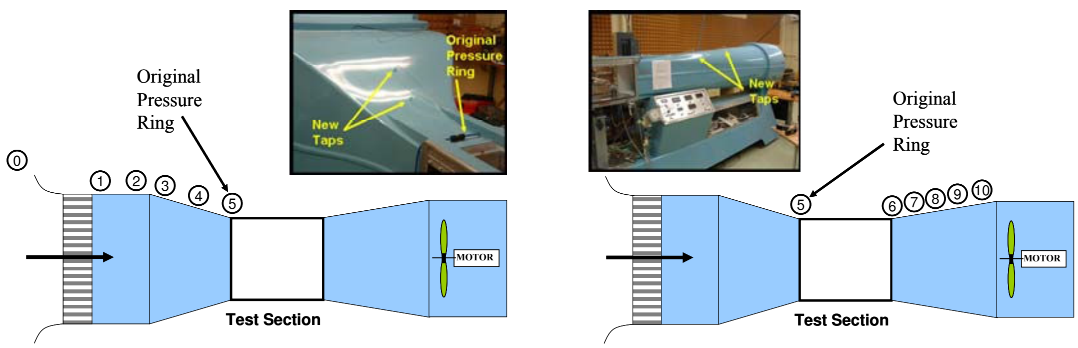
Wind tunnel testing has long been an important component common to many introductory fluid mechanics and aerodynamics courses. Demonstrations of the basic physical mechanisms of viscous and pressure drag associated with the formation of drag forces on various aerodynamic shapes are readily conducted using standard electronic or mechanical balance hardware. Experimental measurements of lift, drag, pitching moment, and pressure distribution on small-scale models likewise play a significant role in supporting basic fluid mechanics theory in such introductory courses. Understanding these physical characteristics is very important to automotive aerodynamic design, for maximizing fuel economy, and in the teaching of basic principles of aerodynamic design as applied to aircraft. In addition to the more common use of the wind tunnel as a tool for investigation of the aerodynamics of sting-mounted test models, however, the wind tunnel as a whole provides the means to demonstrate several significant principles of fluid mechanics and the application of these principles to engineering design. One such recent application of the wind tunnel involved instrumenting the entire wind tunnel for pressure distribution measurements, to demonstrate ideal inviscid fluid flow behavior, as well to illustrate the relative importance of various sources of mechanical energy losses to wind tunnel design.

This paper presents the authors experience with modifying an Aerolab educational wind tunnel test facility for experimental work associated with an Undergraduate Campus Internship (CSI) mentoring program project. The purpose of this laboratory activity was to demonstrate characteristics of variable area duct flow and diffuser boundary layer separation using flow visualization by smoke injection. A simple modification to the test section region of the wind tunnel was made to conform to a converging and/or diverging (diffuser) duct flow configuration. This setup was used in conjunction with a special-purpose smoke rake injection system of our own design, and a relatively inexpensive low-power laser-based lighting system, for visualization of the associated air flow. The paper describes various ways of constructing and testing simple duct flows for the wind tunnel test section region using inexpensive materials, as well as the requirements for obtaining good quality flow visualization using smoke injection. The smoke visualization tests can potentially reveal the details of inviscid streamline flow for converging ducts or channels and the onset of boundary layer separation, along with various flow instabilities associated with discharge from a low-speed diverging (diffuser) duct outlet. The connection between diffuser and nozzle head loss behavior and boundary layer separation phenomena are also brought out in these experiments, and they should be adaptable to most educational wind tunnel laboratory test facilities.

Introduction

The educational wind tunnel represents an important tool for introducing engineering students to basic experimental measurements of lift, drag, pitching moment, and pressure distribution (or pressure coefficient), usually first encountered in the setting of an introductory course in aerodynamics or a junior level course in fluid mechanics. In addition to providing quantitative aerodynamic measurements, the wind tunnel and its companion the water tunnel, offer the ability to visualize the important physical characteristics of fluid flows. In the case of wind tunnel flow visualization, smoke injection is the usually means to visualize the flows, whereas with water tunnel flow visualization a dye injection method is typically employed. The ability to visualize of external flows, and the associated boundary layer separation phenomenon, forms an extremely important thrust of such introductory courses, and is an invaluable educational tool as well as a tool for practical engineering design.

In contrast with external flows, the investigation of internal flows, either qualitatively using flow visualization or quantitatively, is not typically associated with wind tunnel measurements. In addition to the more common use of the wind tunnel as a tool for visualization of external boundary layer flows on sting-mounted test models, however, the wind tunnel itself provides a means to also demonstrate internal flow phenomena. With the proper setup, it can provide an excellent demonstration of both ideal inviscid duct fluid flow behavior, as well as the affect of mechanical energy losses associated with internal boundary layer separation phenomena.



(a) Inlet Pressure Taps **(b) Outlet Pressure Taps**

Figure 1: Simple Wind Tunnel Pressure Tap Modifications

Recently a simple means to modify existing educational wind tunnel facilities was presented and used to successfully demonstrate certain duct flow (stream tube) principles related to wind tunnel design.[1] Typically commercially-available wind tunnels come equipped with standard pressure taps for sensing the test section pressure level. To complement this approach, simple inexpensive modifications were made to an existing wind tunnel facility, so that the entire wind tunnel could be used to further illustrate these important design principles. The modifications involved the addition of inexpensive pressure taps to give a detailed picture of the distribution of pressure along the entire wind tunnel. Simplified views of these simple pressure tap modifications are shown in Figures 1(a) and 1(b) for the regions upstream and downstream of the test section area, respectfully. This work readily showed that the major source of these losses is associated with the diverging (diffuser) section, in obvious contrast to the converging inlet section.

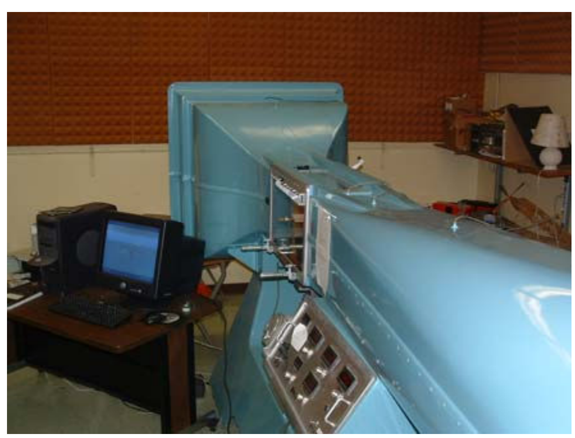
The objective of this paper is to further illustrate the use of the entire wind tunnel as a test model and to investigate, using laser-based flow visualization techniques, internal flow phenomena and the associated internal boundary layer separation characteristics. In addition, this work involves mentoring an undergraduate mechanical engineering student as part of a CampuS Internship Program (CSI) project. The CSI program is designed to give first year students the opportunity to participate in academic research in their discipline early in their college careers.[2] CSI students participate in a variety of projects with research teams throughout the College of Engineering. The students worked in labs, testing facilities, and on their own to learn what academic research is like. The CSI Program is one of six initiatives that are funded by STEP. STEP (Science, Technology, Engineering, and Mathematics Talent Expansion Program) is supported by the National Science Foundation's STEM (Science, Technology, Engineering, and Mathematics) Talent Expansion Program.

The modifications to the existing wind tunnel facility take the form of test section inserts, which can be constructed from inexpensive materials to form a wide variety of different nozzle or diffuser geometries. To visualize the streamline flow, a simple smoke rake has also been designed to produce a set of uniformly spaced smoke streams which can then be introduced into the inlet of the test section region, upstream of the nozzle or diffuser model. The entire flow of the wind tunnel proceeds through the partially blocked off test section, producing the desired internal flow field and boundary layer separation behavior. The important features associated with the design of the smoke rake and it's associated smoke injection system are presented along with suggestions for properly visualizing the flow fields. The laser illumination and streamline image capture system is described, along with a relatively simple camcorder image acquisition setup for filming the streamline flows. The streamline flow visualization results are illustrated for a uniform duct flow (open test section) and for a converging nozzle geometry with a sharp-edged transition. This is but one of the basic duct flow geometries that are currently under investigation for this project. The undergraduate student is involved with all phases of the work, including the design and construction of the duct flow models and the acquisition and processing of the flow visualization images.

Wind Tunnel Facility

Figure 2 shows the existing Educational Wind Tunnel associated with the current development. A photograph of the overall facility is shown in Figure 1(a), and a longitudinal view of the wind tunnel showing the test section and instrumentation for data acquisition is shown in Figure 1(b).

(a) Wind Tunnel Facility



(b) Test Section and Instrumentation

Figure 2: Educational Wind Tunnel Facility

While relatively inexpensive in comparison to some wind tunnels, this facility has been demonstrated to be capable investigating a wide variety of phenomena of interest to fluid mechanics and aerodynamic courses.[1,3-5] The wind tunnel has a test section measuring approximately 12 in x 12 in x 24 in (305mm x 305mm x 610mm), and has a maximum air speed of approximately 140 mph (63 m/s). It is instrumented with an electronic strain-gage based balance for measurements of normal force, axial force, pitching moment, and pressure distribution as a function of air speed and angle of attack. Both manual as well as electronic pressure sensing is available on this facility. Figure 3(a) shows a photograph of the manual valve used to select individual pressure tap lines on the existing facility. An electronic pressure scanning unit containing 32 individual electronic pressure sensors is also used in conjunction with this facility. This latter unit can be use to provide real-time visualization of the pressure distribution in the wind tunnel, using the external pressure taps shown earlier in Figure 1, in much the same manner as it has been used to visualize the pressure distribution associated with airfoils and wings.[3,5] Manual measurements are accessible from a front panel digital display shown in Figure 2(b), and electronic data acquisition is also available for remote access and real-time measurements. For the purpose of the current investigation, additional flow visualization hardware has been developed to augment that which has been used previously in experimental work. Key to the flow visualization system is the smoke rake and the associated smoke distribution system which are described below.

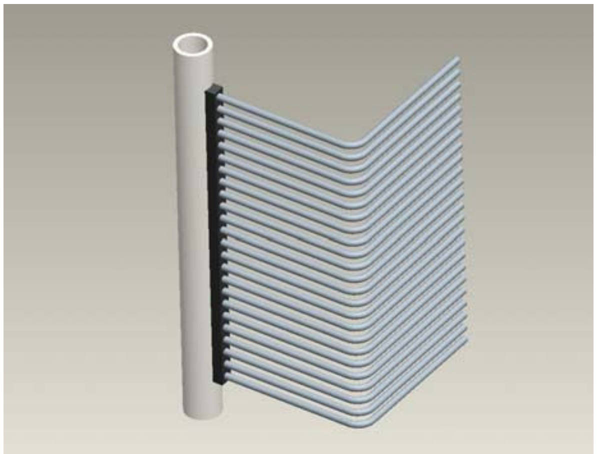
Smoke Rake System

Smoke rakes are for some reason not readily available commercially for the existing educational wind tunnel facility. Single stream smoke injection is available, but does not provide the desired streamline detail. Hence, a general-purpose smoke rake flow visualization system was designed for our facility, and should also be applicable for similar wind tunnels. Figure 3 is a CAD drawing of basic the smoke rake developed and used in the current investigation. Figure 3(a) shows an overall view of the rake with a series of flow tubes which distribute the smoke from a cylindrical manifold assembly. The rake has been designed to be modular with a variable number of tubes. In addition, the spacing between tubes is also variable by selectively removing and blocking ports in the manifold bracket. In the current version used for testing presented below, the rake was configured into a total of eleven ¼-inch (6.4 mm) O.D stainless steel tubes. Smaller or larger tubes can be used, depending on the size of the test model. This size provides reasonable resolution of the flow fields associated with the internal flows currently under investigation.

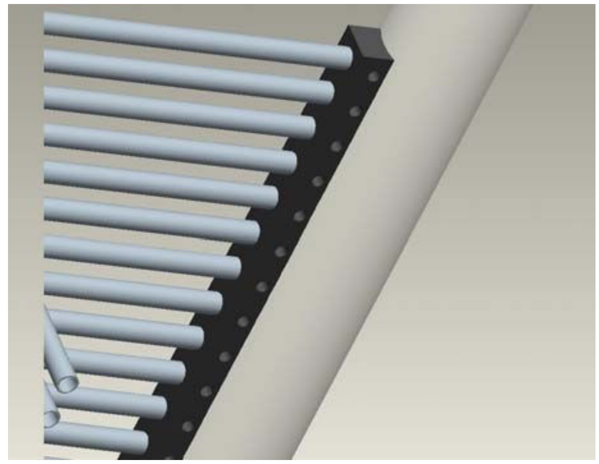
There are a number of important issues to be considered in the design of a smoke rake flow visualization system, and a complete discussion and engineering analysis of all of these in detail could easily form an additional paper. Some of the main issues include the following:

- Number of streams and diameter of tubes.
- Length of tubes and radius of bend to align with flow.
- Design of manifold assembly and mounting of tubes.
- Balancing of injected smoke flow with outer flow stream.
- Level of turbulence in wind tunnel.
- Flow development inside the smoke rake tubes.

- External boundary layer development on smoke rake tubes.
- Tube wall thickness and geometry of exit port.
- Mounting of the rake in the wind tunnel test section.



(a) Smoke Rake Assembly



(b) Close-up Detail of Manifold Bracket

Figure 3: Smoke Rake

To provide good flow visualization and streamline definition, laminar flow in the rake tubes is highly desirable. Otherwise, the smoke streams will break up very quickly after exiting the tubes, which will "wash out" the desired streamlines. Well defined streams on the order of 12 inches (30 cm) or more are possible with careful attention to this laminar flow requirement, and with proper balancing of the flow streams.

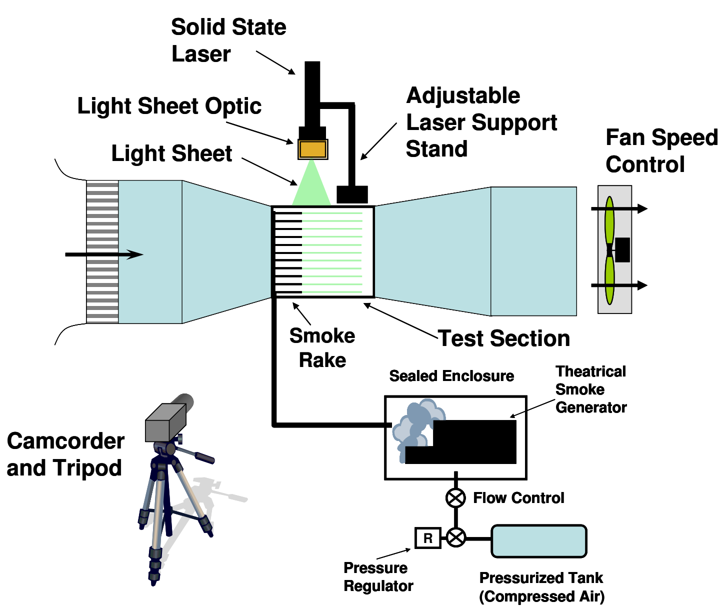


Figure 4: Smoke Distribution System

The diameter and length (in external flow direction) of the flow injection tubes also limits the tube spacing. Too close and the external boundary layers from adjacent tubes will interfere, and also tend to block off the flow around the entire rake assembly.

Smoke Generation System

In addition to the rake itself, a smoke generation and smoke distribution system is required to supply smoke at a constant rate to the rake assembly. A schematic diagram of the current smoke distribution system is shown in Figure 4. Flow must also be provided through the test section. The flow velocities required to provide well-defined streamlines are considerable below the normal wind tunnel airspeeds. Hence, an external box-fan was positioned at the discharge end of the wind tunnel to suck air and provide the flow. A Variac (variable transformer) was used to regulate the speed of this fan, and the relative spacing between the fan and the exit plane of the wind tunnel also provided some speed adjustment. In practice, a spacing of about 6 inches (15 cm) was sufficient for testing of the current duct configurations, but this would depend on how severely the test section flow was being blocked off. Another issue of importance to more quantitative evaluation of the flow visualization is the determination of the airspeed or flow rate in the duct model. The airspeeds are too small for the normal wind tunnel measurement system which makes use of the pressure drop in the wind tunnel converging section resulting from the Bernoulli effect. An indirect method is possible, by measuring the volumetric flow rate supplied to the rake manifold from the smoke generation system. If the total volumetric flow rate of air containing smoke is Q, then the average discharge velocity from N identical rake tubes will be $U = Q/(NA)$, where A is the internal cross-sectional area of a single typical rake tube. Since the exit tube flow must be properly balanced with the external airspeed for so-called iso-kinetic injection, U will be approximately the airspeed in the tunnel test section at the point of the smoke rake exit. Alternatively, a small rotating vane anemometer could possibly be placed in a neutral location, depending on the type of test section model configuration. For the current testing, the volumetric flow rate was less than about 10 SCFH (280 liters/hour). The ¼-inch 11-tube stainless steel rake tubes have an inside diameter of about 0.200 inches (0.508 cm), which yields a nominal airspeed of about 1 ft/sec (0.4 m/sec).

Figure 5: Overall Experimental Setup

Streamline Illumination and Image Acquisition System

For clear visualization of the smoke streams, an illumination system is also needed. Figures 4 and 5 also show the laser-based illumination setup used for the current testing. A 500mW solid state laser was mounted vertically on an adjustable support platform. The platform provided lateral displacement adjustment and tilt adjustment degrees of freedom for aligning the light sheet with the plane of the smoke streams. A simple cylindrical lens optic produced the desired sheet of light for illumination of a section of the test section. The top of the test section, as well as the side-walls, are of Plexiglas for optical access. Not all of the flow field could be viewed at the same time with the current optical setup due to the spreading of the laser light sheet. For safety reasons, precautions were taken to minimize stray laser reflections. Test models were constructed from flat black opaque and diffusely scattering materials for this reason. Figure 5 shows a photograph of the overall experimental setup, including the image acquisition setup. A generic camcorder with tripod mount was used to capture both video and single frame images of the streamline flow. The camcorder was positioned about 10 ft (3 m) from the image plane to minimize parallax effects and to also provide large depth of field to keep everything in focus. It should be noted that the camcorder is shown somewhat closer in the above Figure. A paper grid rear-lit with an incandescent lamp provided the background grid shown in Figure 6(b).

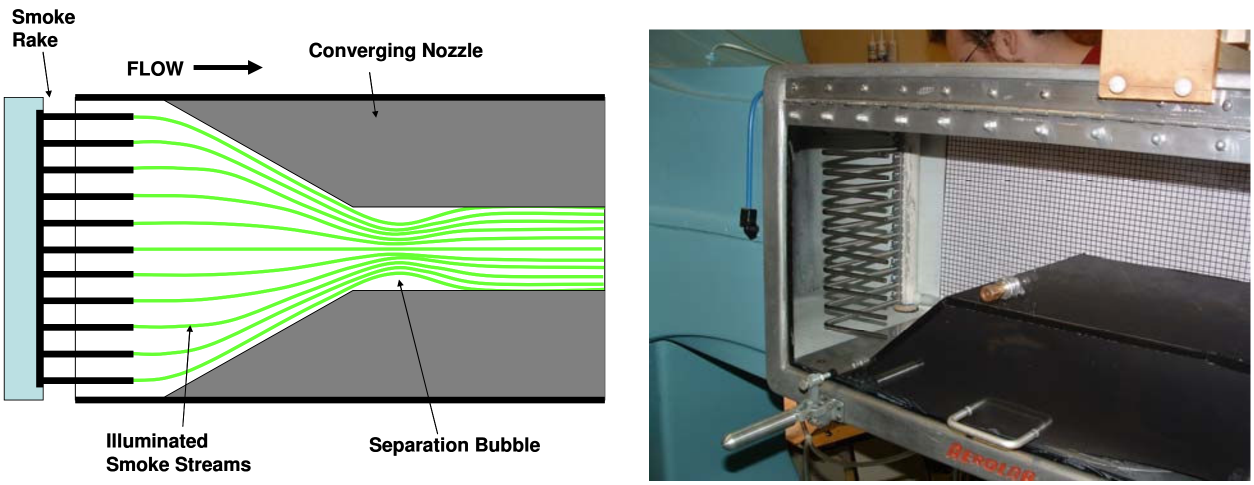
Test Section Duct Flow Model Results

A wide variety of test section geometries can be implemented for visualization of internal duct flows. For the present, we will illustrate two cases: (1) Uniform flow in the wind tunnel, and (2) Flow in a sharp-edged converging duct. Figure 6(a) shows a schematic diagram of the ideal uniform streamline flows exiting the smoke rake, and Figure 6(b) is a photograph of the illuminated actual streams exiting from the smoke rake located in the uniform free stream flow with the test section region empty. Note that the streams are quite well-defined, but clearly not perfectly uniform. Care must be taken to properly position the rake in alignment with the flow, as well as to adjust the smoke injection flow in balance with the airspeed. Otherwise, instabilities in the smoke streams will result in either quick breakup of the streams, or meandering of the streams.

(a) Ideal Smoke Rake Streams **(b) Actual Smoke Streams**

Figure 6: Smoke Rake Testing in Uniform Flow

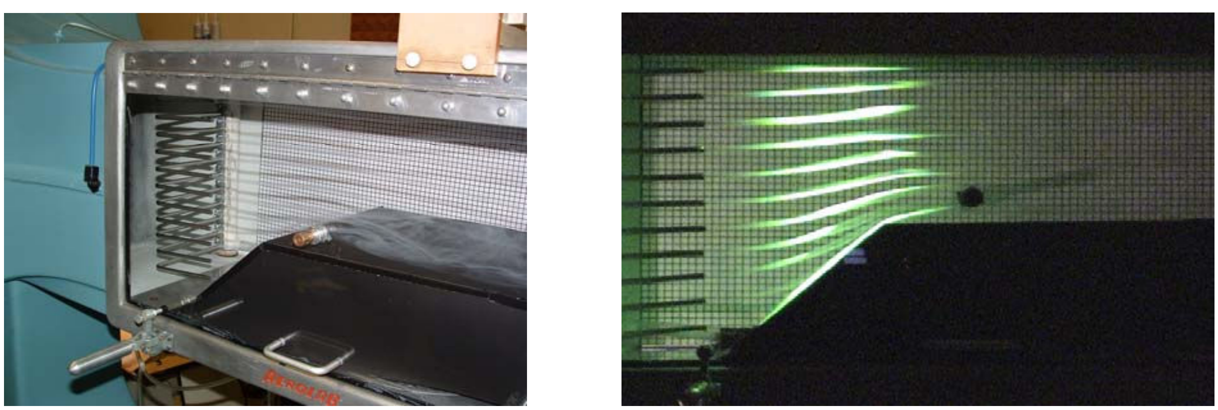
Air currents caused by the room air-distribution system or movement of individuals near the wind tunnel entrance or exit can significantly affect the steadiness of the streams. Slight ambient pressure changes in the room can affect the flows as well, such as might result from nearby doors opening or closing—even if not in the same room. With proper attention to these details, and with a little patience, it is relatively easy to achieve good results.



(a) Drawing of Sharp-Edged Nozzle **(b) Actual Half-Section Nozzle**

Figure 7: Sharp-Edged Converging Nozzle Test Model

Figure 7(a) shows a schematic diagram of a sharp-edged converging nozzle, and Figure 7(b) shows the version this model installed in the wind tunnel test section region. Note that in the actual model, only half of the nozzle was constructed for simplicity. This allows ready access for the light sheet through the transparent top of the wind tunnel. It is also relatively easy to construct a transparent slit in the upper wall of the duct using a celluloid sheet window, for testing of full symmetrical duct models.



(a) Nozzle Streamlines in Room Lighting **(b) Streamlines with Laser Lighting**

Figure 8: Converging Nozzle Streamlines

Figure 8(a) shows the streamlines exiting the smoke rake and entering the sharp-edged converging nozzle test model. Here, even though only room lighting is used, the streamlines are still readily visible as they enter the model, and boundary layer separation is clearly evident at the sharp edged transition. The converging of the streamlines as they enter the narrowing nozzle region is also clearly evident. Some meandering of the streams results in loss of illumination in adjacent streams in still-frame captures, but the flow characteristics are still clearly evident in live video. Spreading or dithering of the light sheet could be used to enhance the definition of the still-frame captures, or alternatively this could be done through the use of frame averaging.

The results thus far are very encouraging, and numerous other duct flow test sections are currently planned for testing. The construction materials are very inexpensive—typically generic flat black finish foam board, which is available form any art supply store. Flat black duct tape was used to temporarily attach the duct model to the inside of the tunnel wall, and the model is easy to remove and install. Side seals are not critical, although some attention to stray leaks can also affect the meandering or stray movement of the smoke streams. For better sealing against the removable side panels of the test section, weather stripping works quite well.

These test results, and the techniques presented here, should be very useful in providing physical insight in undergraduate fluid mechanics courses, as well as in more advanced courses dealing with boundary layer separation. The possible course applications of the hardware discussed in this paper include laboratory enhancement for the undergraduate fluid mechanics laboratory, the introductory aerodynamics laboratory, and practical laboratory experience associated with more advanced graduate level boundary layer theory courses. Specific learning objectives associated with this type of laboratory experience include the following:

1. Introduce students to practical optical fluid flow visualization techniques.
2. Develop understanding of engineering fluid mechanics principles associated with wind tunnel smoke rake design.
3. Develop experimental understanding of laminar and turbulent jet flows associated with smoke injection into airstream.
4. Introduce students to streamline flow for ideal (inviscid) converging and diverging ducts.
5. Develop understanding of engineering fluid mechanics principles associated with boundary layer separation for sharp-edged converging duct (nozzle).
6. Develop understanding of engineering fluid mechanics principles associated with boundary layer separation for diverging duct (diffuser) flows.
7. Develop understanding of the modeling limitations of the inviscid flow approximation.
8. Foster an important hands-on wind tunnel laboratory experience.
9. Develop a basic understanding of the relationship between duct flow boundary layer separation and airfoil boundary layer separation phenomena.

Summary and Conclusions

This paper presents the authors recent experience with a simple flow visualization modification for use in conjunction with an existing Aerolab educational wind tunnel test facility. This facility is generally used for experimentation to complement theoretical work associated with both junior-level Fluid Mechanics (ME571) and senior-level Aerodynamics (ME628) courses. The current work is an outgrowth of an undergraduate student CSI mentoring project, and should complement previous experimentation associated with these courses, as well as being useful for graduate level courses dealing with complex boundary layer separation phenomena. An inexpensive method of constructing simple and functional internal duct models was presented, which could be incorporated into virtually any educational wind tunnel facility. In addition, a simple design for a general purpose smoke rake was introduced and tested with good results.

The connection between diffuser frictional loss behavior and boundary layer separation phenomena associated with the re-circulating flows in the observed separation bubble is also brought out in these experiments. Future additions planned include the testing of more complex duct flow inserts, and refinement of the smoke rake and the image illumination system to extend the range and clarity of image captures. A modular smoke rake is envisioned which can be adapted to several different test model geometries. Comparisons can then be made to a number of different nozzle and diffuser flow configurations.[6,7]

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