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Construction of a Smoke-wire Rig for Visualization of Complex Three-Dimensional Flow*

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This paper describes the construction process of a smoke-wire rig for visualization of complex three-dimensional flow undertaken by a group of second-year undergraduate students during their In House Practical Training (IHPT, project module) at the School of Mechanical and Production Engineering, Nanyang Technological University. The rig was designed, constructed and tested within a period of 3 weeks. The main objective of the project is to provide an opportunity, in addition to normal lectures and tutorials, for the students to acquire some ideas in designing a wind tunnel that incorporates some of the most commonly used flow visualization techniques, namely the smoke-wire and laser-sheet methods. Some important fundamental fluid mechanics concepts, such as two- or three-dimensional flows, can be introduced to the students through the visualization of the flows behind a splitter plate consisting of a convoluted trailing edge.

AUTHOR'S QUESTIONNAIRE

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in:
   Teaching of undergraduate fluid mechanics, aerodynamics and hydrodynamics courses. Based on the authors' teaching experience, one of the most common problems associated with these subjects is the ability of the students to visualize the flows. The visualization is an important supplement to the lectures.
2. The paper describes new experiments useful in the following courses
   Undergraduate aerodynamics and fluid mechanics and final-year projects.
3. Level of students involved in the use of the equipment
   Second to final year undergraduates depending on depth of treatment. Flow visualization using laser-sheet techniques is of postgraduate level and needs instructor guidance at the undergraduate level.
4. What aspects of your contribution are new?
   The effective combinations of design, construction and testing with a small wind tunnel in a single project.
5. How is the material presented to be incorporated in engineering teaching?
   Either as described in the paper or as three separate final year projects.
6. Which texts or other documentation accompany the presented materials?
   Mainly the texts *Low-speed Wind Tunnel Testing* (A. Pope) and *Fluid Mechanics Measurements* (R. J. Goldstein).
7. Have the concepts presented been tested in the classroom? What conclusions have been drawn from the experience?
   This paper reports the outcome of a project undertaken by second-year undergraduate students. Although the detailed calculations on pressure loss of the wind tunnel components are not being emphasized, it shows that projects like this provide useful opportunities for students to acquire basic criteria in designing wind tunnels and common flow visualization techniques, namely the laser-sheet and smoke-wire methods.
8. Other comments on benefits of your presented work for engineering education
   In most laboratory sessions in fluid mechanics, aerodynamics and hydrodynamics, the main focus would be on measuring quantities such as pressure and velocity and only by observing the variations of these quantities, with space or time, can a general picture of the flow be obtained. Direct experience is lacking. In our approach the visualization enables better understanding of flow phenomena and their mathematical representation.

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INTRODUCTION

ONE OF the most common problems associated with undergraduate learning in fluid mechanics, hydrodynamics or aerodynamics lies primarily in the inability of the students to see 'physically' the materials presented to them. In many situations, the interpretation of a particular flow field, e.g. flow over an airfoil at different angles of attack or flow through a curved bend, has to rely on the use of mathematical representation, such as partial differentiation. This has complicated further the learning process. Moreover, in most laboratory sessions on fluid mechanics, the main focus is on measuring quantities such as pressure and velocity; only by observing the variations of those quantities, with space or time, can a gross picture of the flow field then be obtained. Thus, direct experience is lacking. In this respect, visualization of the flow field would certainly facilitate the understanding of flow phenomena and, consequently, the relation with their mathematical representation [1]. This project is devised in such a way that some important fundamental fluid mechanics concepts can be conveyed to the students through flow visualization using the simple smoke-wire technique.

The In House Practical Training (IHPT) program at the Nanyang Technological University, which starts after the second-year examination, is meant to provide opportunities for students to gain hands-on experience in most of the engineering hardware available at the university, which generally resembles machines currently in use in industry. The training period, which lasts 10 weeks, consists of subject modules (such as CNC and CAD/CAM) as well as project modules. Such a training program not only enhances the students' adaptability to industry after their graduation from university but also provides a useful opportunity for them to explore new phenomena and experience. Details of the training program have been described previously [2].

In this particular project module, the flow field of a splitter plate consisting of a convoluted trailing edge (commonly known as lobed forced mixer) is chosen mainly because in previous research literature (including a on-going research project at the School of Mechanical and Production Engineering), e.g. [3, 4] the flow upstream of a convoluted trailing edge is essentially two-dimensional but becomes three-dimensional after passing over the convoluted trailing edge (see Fig. 1). The mixing process of the two streams on either side of the lobed mixer is believed to have taken place within six to seven wavelengths (wavelength of the convoluted trailing edge shape, see Fig. 2) downstream of the trailing edge. Students should have an appreciation of the difference between the two-dimensional and three-dimensional flow fields, as well as the evolution of the flow from two-dimensional to

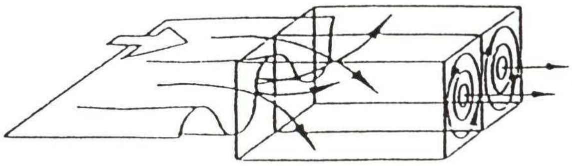
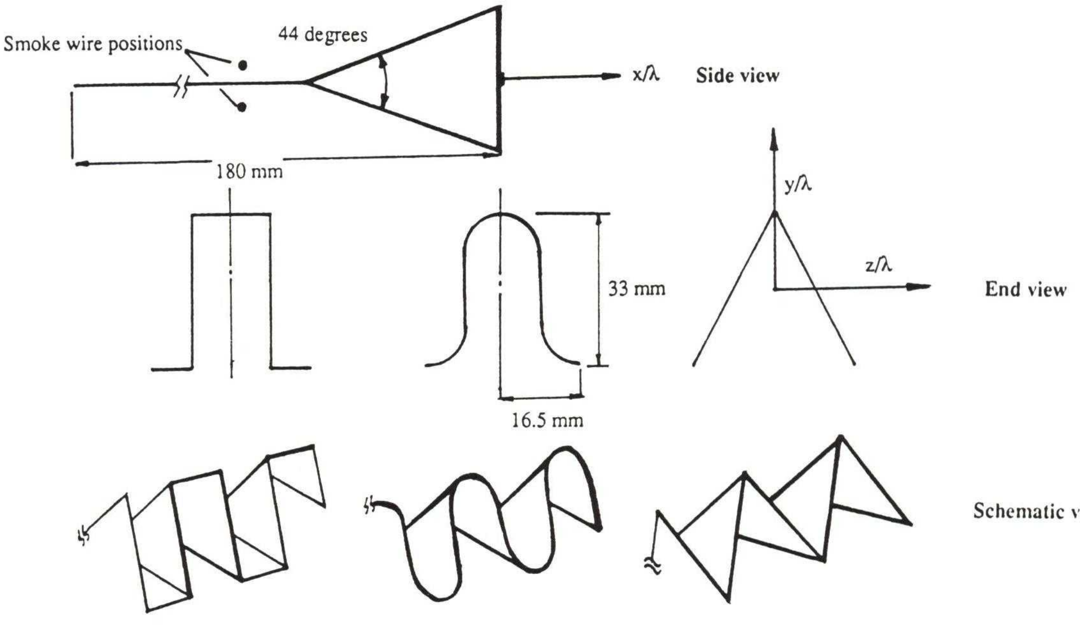


Fig. 1. Wake flow structure behind the convoluted trailing edge (taken from ref. [3]).



(a) Square wave (b) Semi-circular wave (c) Triangular wave

Fig. 2. Lobe configurations under investigation.

three-dimensional due to the convoluted trailing edge. One of the most common engineering applications for such device is in aircraft gas-turbine engine exhausts, where the mixing of the core and bypass flows can greatly reduce the noise level emitted by the engine.

The flowing section describes the design considerations and the time allocation for the project, including the concepts and ideas expected to be acquired by the students at different stages. Some visualization pictures obtained by the students will then be presented. The paper ends with brief concluding remarks.

RECOMMENDED WORKING SCHEDULE AND DESIGN CONSIDERATIONS

The project should be finished within 3 weeks; $5\frac{1}{2}$ working days per week, i.e. from Monday to Friday, 9.00 a.m. to 5.00 p.m. and Saturday, 9.00 a.m. to noon. The number of students involved in this project is about 10 with one technician from the workshop to assist the machining of parts. The 3-week training period is further subdivided into three stages as listed in Table 1.

Table 1. Recommended working schedule

First week	Planning, designing and part drawing (sketch)
Second week	Fabrication of the wind tunnel including the testing of the flow qualities inside the wind tunnel
Third week	Flow visualization tests and result presentation

The following information is also given to the students at the beginning of the project.

1. To design, construct and test a small wind tunnel suitable for visualizing flow behind a splitter plate with a convoluted trailing edge, i.e. the lobed forced mixer. This is followed by a brief introduction to the lobed forced mixer and some of its common engineering applications [3, 5].
2. The tunnel can be either a blowing or a sucking type. The tunnel test section should be large enough to accommodate the lobed mixer (dimensions are fixed). Different configurations of lobed mixer can be replaced conveniently from the test section for testings. Bulk mean tunnel speed should be within the range 1–3 m/s. The flow velocity on either side of the lobed mixer may be varied so that a velocity ratio can be created, e.g. 1 : 2. This is followed by a brief introduction to various types of wind tunnel available at the university including the functions of the contraction section, diffuser, honeycomb and wire mesh, etc. [6].
3. To fabricate a smoke-wire system for the wind tunnel including a convenient manual mechanism for oiling the wires after each test. This is followed by a brief introduction to various methods for flow visualization including their limitations [8].

Raw materials available for the project are listed in Table 2. The lobed forced mixer has three different configurations, namely square wave, semi-circular wave and triangular wave (see Fig. 2). They are made of fiberglass and the dimensions of the plates are similar to those used previously by Yu *et al.* [4] for velocity measurements. Finally, the students are also reminded that both the dimensions of the lobed mixers and the fan diameter are fixed and their design considerations should be aware of these two constraints. The total budget for the present project is well below $500 Singapore dollars.

Table 2. Raw materials available for use

1. Perspex sheet (thickness 5 mm, 5 ft × 10 ft, one piece)
2. Perspex sheet (thickness 2 mm, 5 ft × 10 ft, one piece)
3. Drinking straws (three packs, 100 each, size: length/diameter ratio ~10, act as the honeycomb)
4. Fine metal screen (3 ft × 3 ft, approximately 30 holes/cm, 0.43 mm diameter wire, one piece)
5. Power supply: AC/DC transformer (240 V/15 V, 0.7 A) and on/off switch
6. Fine stainless steel wire (one roll, diameter 0.05 mm and specific resistance 100 Ω/m)
7. Fan (320 mm in diameter) with variable speed control. (This type of fan is normally used for electronic circuit cooling purpose, Sanyo Denki model 109-313, 0.14–0.11 A, maximum 25 W, single phase)
8. Lobed forced mixers (three pieces, fiberglass, manufactured by an outside contractor)

FINAL DESIGN AND TESTING RESULTS

Final design

The final tunnel design by the students is shown schematically in Fig. 3. A suction type design is preferred. The main components of the wind tunnel are indicated in the figure and their corresponding design criteria are listed below.

Diffuser. Since the diameter of the fan is fixed and the cross-section of the test section is 100 mm (height) × 180 mm (width), a straight diffuser with a divergence angle of 5° is used to connect the end of test section to the fan (with the ratio of the diffuser length to the diffuser inlet height kept below 3). Based on the information provided in ref. [7], the 5° divergence angle is unlikely to cause separation within the diffuser. The diffusion effect appears only on two sides (top and bottom).

Test section. Since the size of the lobed mixer is fixed, the test section is designed to have a rectangular shape with dimensions 100 mm (height) × 180 mm (width) × 700 mm (length). Thus, the test section provides an aspect ratio of 1.8. The high aspect ratio reduces the influence of the side walls

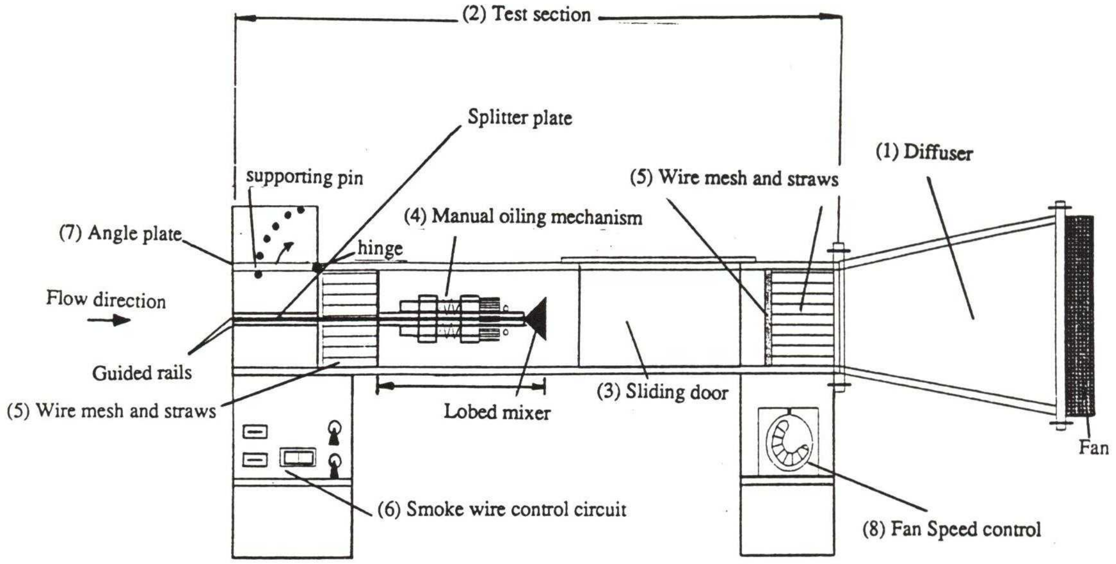


Fig. 3. Schematic view of the smoke-wire rig (not to scale).

so that a two-dimensional flow situation may be achieved. The lobed mixture is mounted at the center of the test section with guide rails located on either side of the side walls. The lobed mixture can be slid freely along the rails (see Fig. 4). An additional splitter plate is placed immediately behind the lobed mixer and is extended to the end of the test section. Thus, the test section upstream of the lobed mixer is being partitioned into two halves where on either side there is the same area of flow.

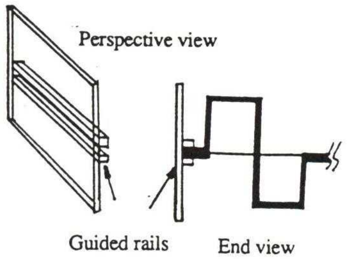


Fig. 4. Schematic view of the lobed mixer guide-rails arrangement.

Sliding door. Following a similar design principle as the mounting mechanism for the lobed mixer, a sliding floor is constructed on one of the side walls. At this position the lobed mixer can be removed easily away from the test section. Special care is taken to avoid any surface discontinuity between the sliding door and the test section (see Fig. 5). Paper gasket is also used between junctions to avoid any leakage of air.

Manual oiling mechanism for the smoke-wires. The mechanism is designed in such a way that the wires can be oiled from one side of the test section by pulling the wires out from the test section using the handles (see Fig. 6). Two wires are installed at a horizontal position with one on each side of the lobed mixer. Weights are hooked onto either end of the wires to straighten them.

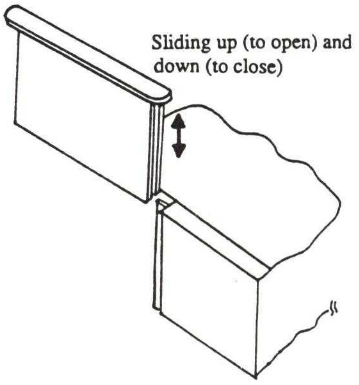


Fig. 5. Sliding door arrangement.

Wire meshes and straws. These are installed initially upstream of the lobed mixer as indicated in Fig. 3. It was observed that during the preliminary visualization tests, a 'bath tub' effect appeared on the flow, which tended to divert towards the side walls. This effect is eliminated by incorporating additional layers of screen and straws at a downstream location, i.e. at the junction between the test section and the diffuser.

Smoke-wire control circuit unit. This is located at one of the supports for the wind tunnel. An on/off switch is used to activate the wires. An additional variable resistor is also implemented so that the current going through the wires can be adjusted to make up for different tunnel speeds.

Angle plate. The angle plate situated at the top end of the tunnel test section is meant to create a velocity ratio between the top and bottom com-

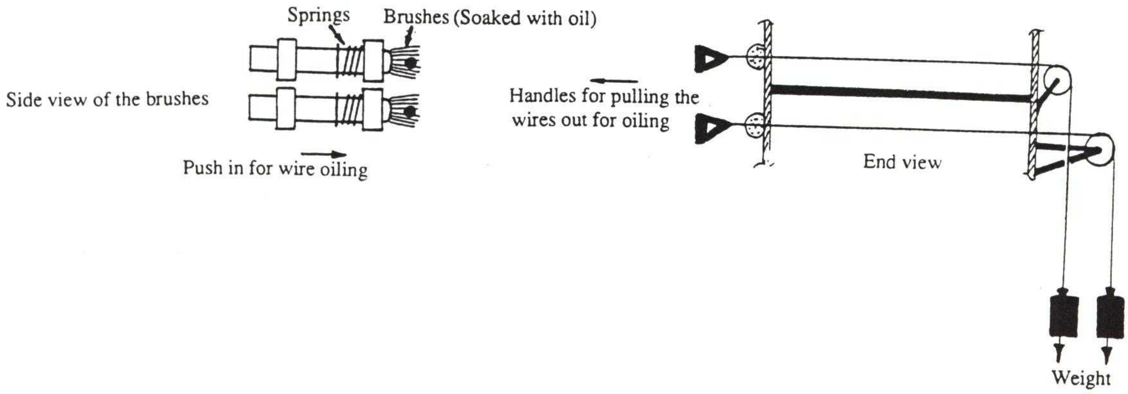


Fig. 6. Manual oiling mechanism for the wires.

partments. The maximum difference in velocity that can be achieved using this arrangement is a ratio of 1:1.3 (with a lower velocity in the top compartment presumably due to a higher pressure loss with the incorporation of a contraction region) with the angle of the plate at about 30° from the horizontal axis. It is believed that the difference may be increased by adding extra wire meshes to the top compartment. However, this has not been tested extensively due to time constraints.

Fan speed control unit. This is situated at one of the supports of the wind tunnel.

Pressure loss calculations and tunnel calibration results

A crude estimate of the pressure loss for various parts in the wind tunnel is also conducted based on the formulae provided by ref. [6], i.e.

Loss due to test section

$$\Delta P_{\text{test section}} = f \frac{L}{D_{\text{H}}} \frac{1}{2} \rho U^2$$

where f is estimated from the formula $f = 64/Re_{D_{\text{H}}}$.

Loss due to the straight diffuser

$$\Delta P_{\text{diffuser}} = K_{\text{diffuser}} \tfrac{1}{2} \rho U^2$$

where $K_{\text{diffuser}} = 0.3$.

Losses due to wire meshes and honeycomb

$$\Delta P_{\text{honeycomb}} = 2x K_{\text{honeycomb}} \tfrac{1}{2} \rho U^2$$

where $K_{\text{honeycomb}} = 0.3$ (two stacks).

$$\Delta P_{\text{wire mesh}} = 4x K_{\text{wire mesh}} \tfrac{1}{2} \rho U^2$$

where $K_{\text{wire mesh}} = 4$ (four layers).

The total loss is found to be about 61.39 Pa based on a tunnel speed of 2 m/s. The power of the fan required to overcome these losses should be $\Delta P_{\text{total}} \times Q_{\text{volume flow rate of the tunnel}} = 2.21$ W, which is well below the power of the fan actually chosen (see Table 2).

The first set of calibration tests are conducted without the splitter plate and the lobed mixer. The angle plate is set at 0°. A standard pitot static tube is used with the output connected to an inclined manometer of accuracy 0.5 Pa. The probe is positioned at the center of the test section. It is found that the most recordable speed for good flow visualization results lies within the range 1.0–2.0 m/s. The Reynolds number based on the smoke wire diameter, 0.05 mm, and the maximum velocity is well below 40, i.e. the wake generated by the wire would be negligible [8]. Thus, this initial speed range should satisfy the requirement for the smoke-wire visualization technique. The Reynolds number based on a tunnel speed of 1 m/s and the hydraulic diameter of the test section is about 8000.

Subsequent tests are performed to determine the steadiness of the fan speed since the fan used here was not designed for wind tunnel applications. Some typical results at a speed of 2 m/s are shown in Fig. 7. Variation in the velocity is found to be within 5% over a period of 60 min. The tests are repeated several times and a similar trend for the speed variation is found. For the present smoke-wire visualization purpose, the process would be less than 1–2 s, special precaution is therefore taken to ensure that visualization tests are conducted after the fan has been switched on for about 15 min and finished within another 10–15 min.

The second set of calibration tests are conducted to determine the uniformity of the flow inside the tunnel. This is measured by traversing the pitot

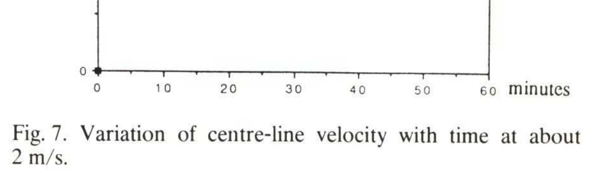
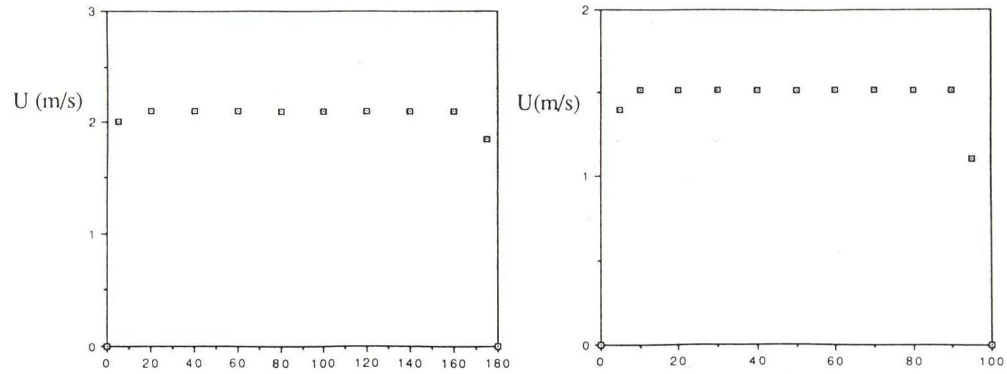


Fig. 7. Variation of centre-line velocity with time at about 2 m/s.



(a) Test section width (mm)

(b) Test section height (mm)

Fig. 8. Velocity distributions at the centre of the test section.

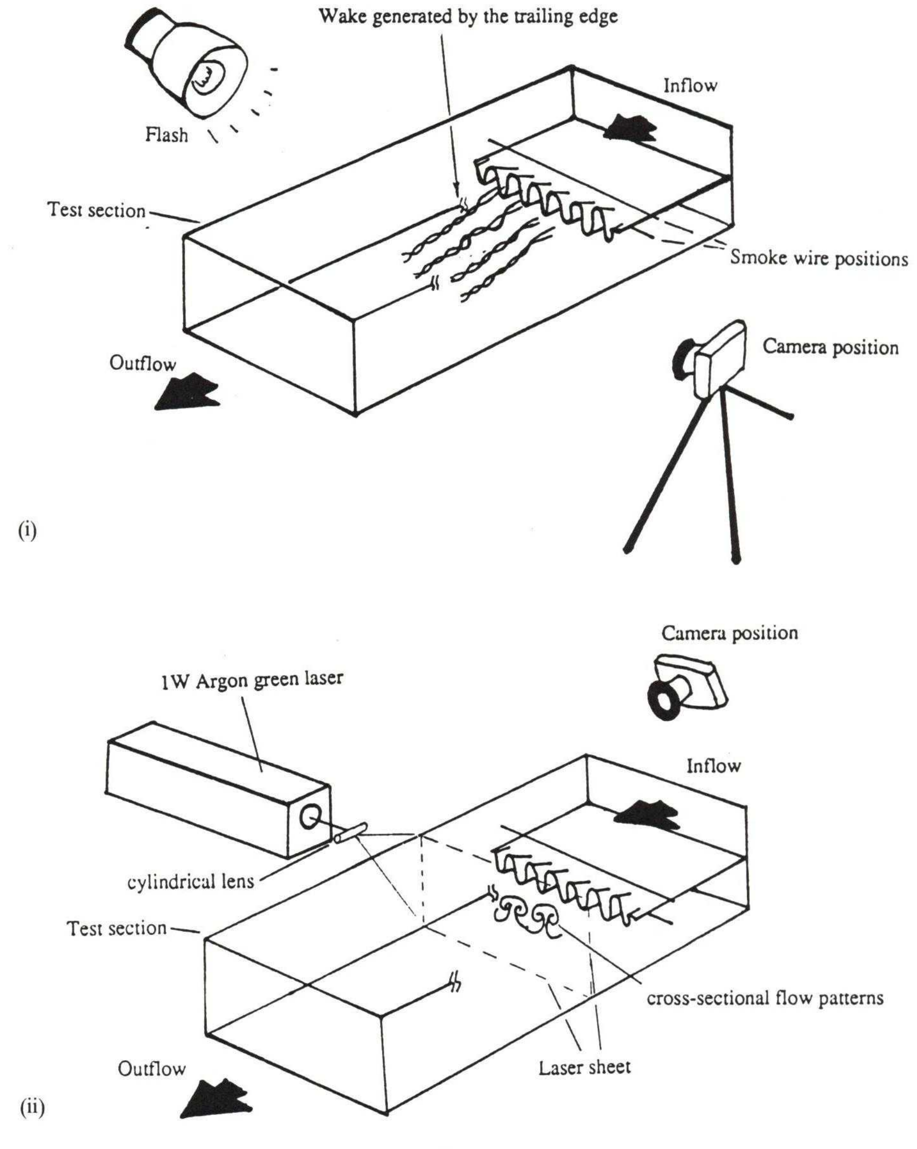
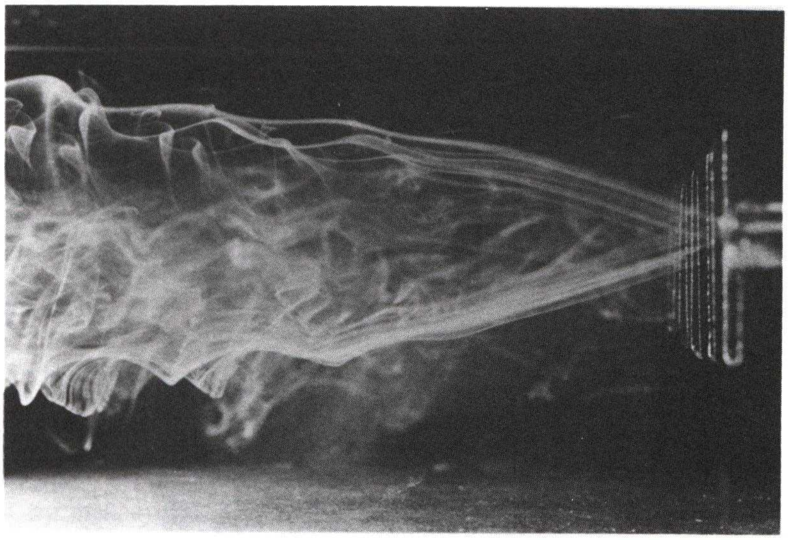
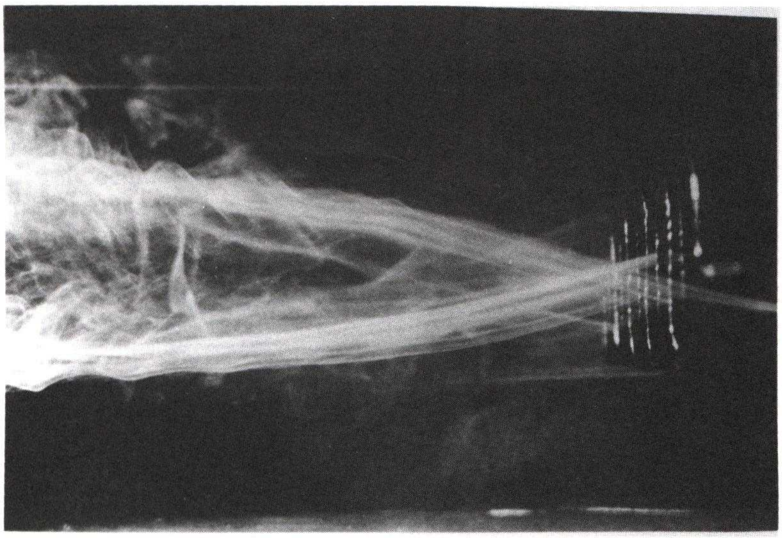


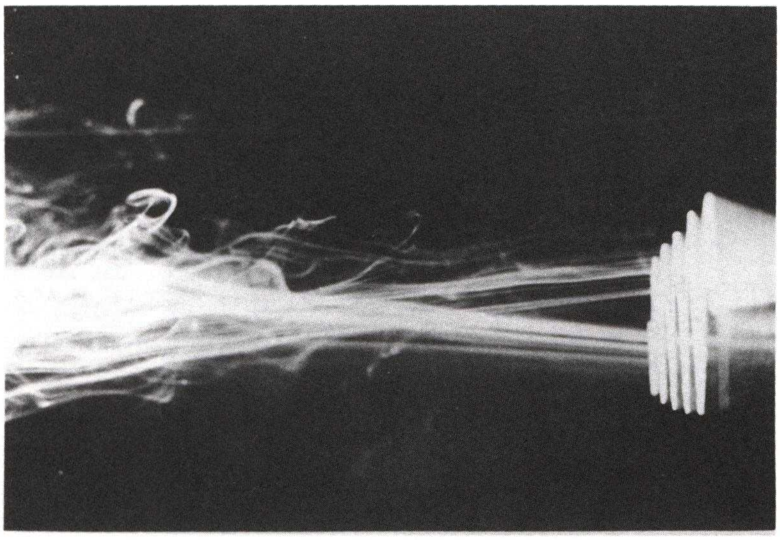
Fig. 9. Flow visualization test arrangement for the wake region behind the lobed mixer; the smoke is illuminated by (i) a multiple flash which synchronizes with the speed of the camera shutter (cf. Fig. 10a–c); (ii) a light sheet formed from a 1 W argon green laser with a cylindrical lens (cf. Fig. 11a–c).



(a) Square wave

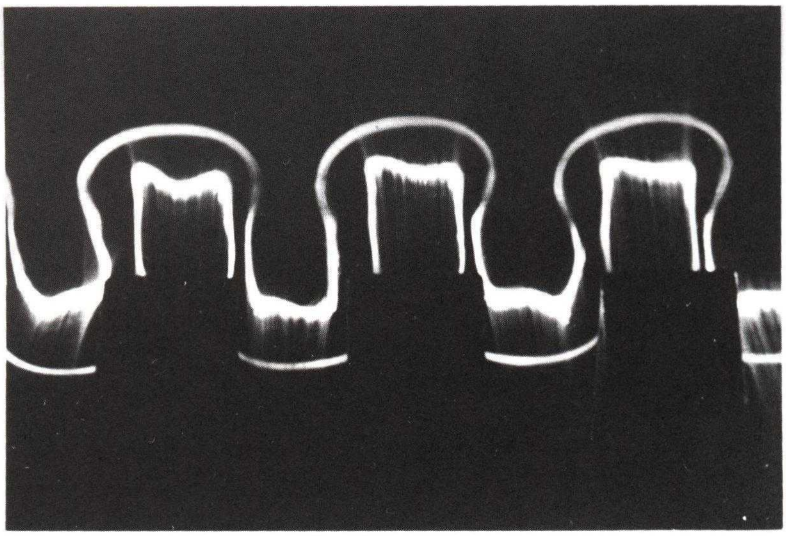


(b) Semi-circular wave

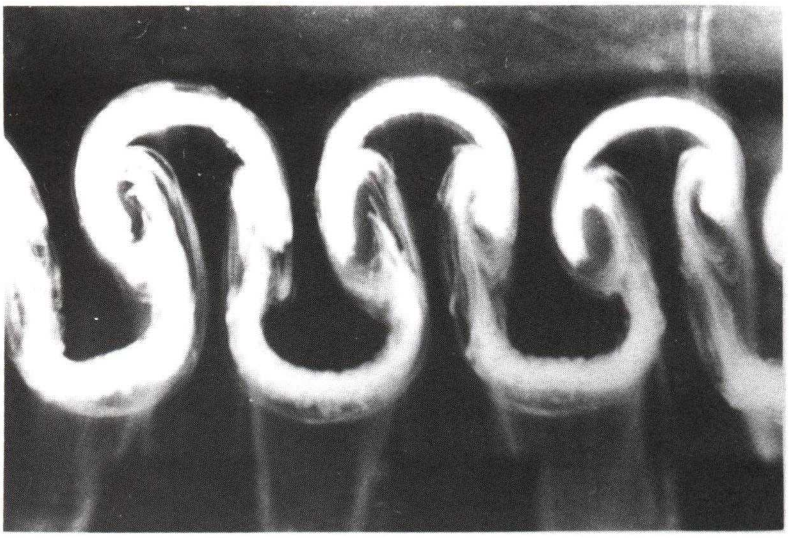


(c) Triangular wave

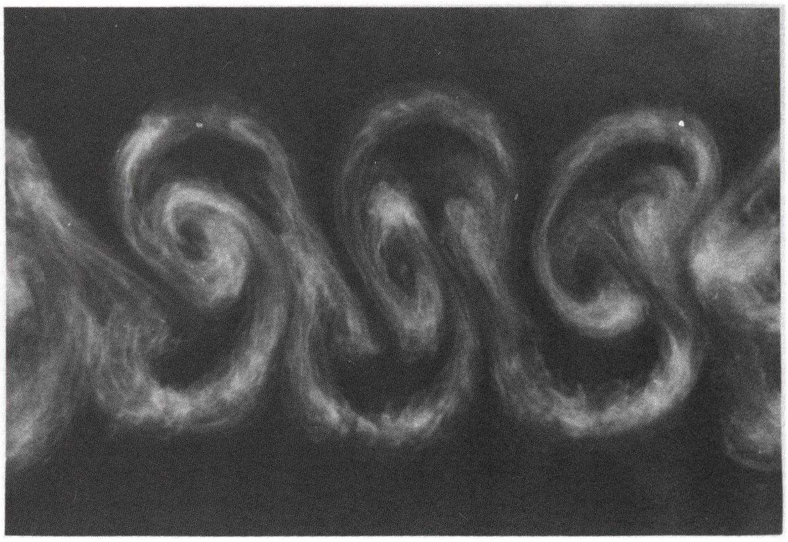
Fig. 10. Visualization of the wake region behind respective lobed mixers.



(a) one wavelength



(b) four wavelength



(c) seven wavelength

Fig. 11. Visualization of the cross-sectional flow patterns at different downstream locations for the square wave mixer (viewing downstream from the trailing edge).

tube along the spanwise and vertical directions of the wind tunnel, with and without the presence of the splitter plate. Figure 8(a, b) shows the distribution of the velocity along spanwise and vertical directions of the test section without the presence of the splitter plate at different speeds. The flow is very uniform with a side wall boundary-layer thickness of about 5% of the tunnel width. Slight asymmetry is also observed and may be largely due to the presence of the guide rails on the side walls (as in the case of Fig. 8a).

Visualization test results

Two types of visualization tests are conducted. Both tests are to visualize the wake region caused by different lobe configurations but at different viewing directions. In the first test, the smoke is illuminated by means of a multiple flash which synchronizes with the camera's shutter speed. Figure 9(a) illustrates the set-up for the visualization test using multiple flashes. Figure 10(a–c) shows the size and structure of the wake region behind respective mixers for a velocity ratio of 1:1. The wake region appears to be largest in the case of the squarewave mixer (Fig. 10a), and in the case of a triangular mixer, streamwise acceleration of the flow immediately behind the lobe is obvious. The acceleration region extends to two to three wavelengths downstream of the lobe trailing edge. The corresponding size of the wake region of the triangular mixer is also relatively smaller than the other two lobe configurations.

Figure 11(a–c) illustrates the cross-sectional flow pattern of the wake for the square lobed mixer at a velocity ratio of 1:1. The visualization test is achieved by illuminating the flow at a particular cross-section of interest using the laser-sheet technique; see Fig. 9(b) for the visualization arrangement. The initial formation of a horseshoe shaped smoke lines shed along the top and bottom of the mixer is clearly shown in Fig. 11(a) at one wavelength downstream of the mixer trailing edge. However, at present, it is not clear why at the regions close to the lobe trough the smoke line appears to be thicker. At four wavelengths downstream of the trailing edge the two lines merge into one, and two counter-rotating vortices are formed at each lobe (see Fig. 11b). By seven wavelengths downstream (Fig. 11c), the enlargement of the vortices and intense mixing by diffusion are obvious. The present observation is found to be in qualitative agreement with the velocity measurements obtained by Yu *et al.* [4].

CONCLUDING REMARKS

The construction process of a smoke-wire rig for visualization of complex three-dimensional flow undertaken by a group of second-year undergraduate students during their IHPT project module has been described. The rig has been designed, constructed and tested within a period of 3 weeks. Although the detailed calculation on respective pressure loss of the wind tunnel components are not being emphasized, it shows that projects of this nature can provide useful opportunities for the students to acquire some important criteria in designing wind tunnels including some of the most commonly used flow visualization techniques, the smoke-wire and laser-sheet methods.

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