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A Low-cost Wind Tunnel Facility for the Visualization of Air Flow Around Buildings*

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The understanding of wind flow patterns around buildings is significant when dealing with wind-induced loading, building ventilation and wind environment around buildings. For teaching purposes, a smoke-generating system in association with a small wind tunnel has been developed to visualize the three-dimensional, non-steady wind flows around different building model configurations. Smoke is generated by feeding mineral oil through metering valves into heated stainless steel tubes. The smoke trace is observed and recorded through viewing windows on the walls of the wind tunnel with the assistance of appropriate illuminator. Detailed information about this visualization facility is provided in this paper. Flow patterns around typical building models are shown along with associated sketches of simplified flow patterns. The facility has been very helpful for the students' learning process in the fundamentals of wind interaction with buildings.

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in:
   The area of wind flow around buildings, wind-induced loading and building ventilation.
2. The paper describes new equipment useful in the following courses of graduate work:
   Building science, fluid mechanics, wind engineering and building aerodynamics.
3. Level of students to be involved in the use of the equipment:
   Senior undergraduate and graduate.
4. What aspects of your contribution are new?
   Details are provided for a *low-cost* wind tunnel facility for the visualization of air flow around buildings; the authors are not aware of any similar facility and flow visualization system covering all aspects of wind flow around different building configurations at this low cost.
5. How is the material presented to be incorporated in engineering teaching?
   Students follow the instructor into the lab and are taught directly all features of wind flow around buildings. They can try different wind directions and/or building configurations alone from a large selection. Thus, they obtain hands-on experience of the subject matter.
6. Which texts or other documentation accompany the presented materials?
   None, in particular. However, depending on the course, the students have already been exposed to the fundamentals of flow separation, reattachment, stagnation, etc. from any text in fluid mechanics or building science (we use the book by Neil Hutcheon).
7. Have the concepts presented been tested in the classroom or in project work? What conclusions have been drawn from the experience?
   Yes, and the experience has been very positive. Students like the facility and gave us an enthusiastic feedback, particularly regarding the hands-on experience part.

Other comments on the benefits of your presented work for engineering education:
The facility described in the paper can be developed at any institution in which the curriculum of engineering programs includes wind engineering, building science or simple fluid mechanics. The budget required is very affordable and the performance of the system serves well the students' learning process.

INTRODUCTION

THE CENTRE for Building Studies was established by Concordia University in Montreal in 1977, for purposes of education, research and applications in building engineering. Through its unique facilities, the centre offers comprehensive educational programmes to undergraduate and graduate students in four main branches of building engineering, namely building environment, building science, building structures and construction management. Wind engineering and building aero-

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dynamics has been a focal area of development and a large boundary-layer wind tunnel was designed and fabricated at the Building Aerodynamics Laboratory to enhance the study of wind effects on buildings and their environment. The wind tunnel has functioned well for both fundamental research and industrial projects on a variety of areas, such as wind loads on buildings, pedestrian-level winds and pollutant dispersion around buildings. However, this large tunnel is difficult to use for teaching purposes. Instead, a much smaller tunnel with a flow-visualization facility was more desirable in terms of accessibility, serviceability and economy. Therefore, with very limited resources, it was decided to develop a small but efficient wind tunnel for the visualization of air flow around buildings.

Teaching concepts related to the air flow around buildings is necessary in a number of courses such as fluid mechanics, wind engineering and building science. Flow phenomena—e.g. separation, reattachment, vortex entrainment, shear layer formation—have to be thoroughly explained to the students for their full understanding of the interaction between wind and buildings. Sketches or slides for particular cases are helpful but they are naturally limited and they lack the three-dimensionality and the flexibility of 'hands-on' experience. An inexpensive smoke-generating system and a set of building model configurations have been developed and operated with a small wind tunnel to demonstrate the airflow interaction with buildings and their environment. In particular, the students learn how different building geometries and configurations can affect natural ventilation; wind forces on buildings; and wind-induced pedestrian discomfort around buildings. The demonstration and utilization of the system helps the understanding of concepts of wind flow around buildings and student learning is enhanced. In addition, the demonstration becomes a memorable experience on the part of the students.

DESCRIPTION OF THE FACILITY

The wind tunnel has been designed and fabricated in our laboratory by considering its special requirements and potential applications. The elevation of the wind tunnel is sketched in Fig. 1. It is an open-circuit, suction tunnel with a fan driven by a 2 h.p. motor. A manually operated damper is designed to control the outlet flow rate and, thus, the wind speed in the tunnel. Between the fan and the working section of the tunnel there is a high-efficiency filter of a square section 0.61 × 0.61 m. The walls of the wind tunnel are made of wood and form a square section with each side having a length of 0.25 m. The main body of the wind tunnel consists of four sections, each 0.61 m long. Two Plexiglass viewing windows are set on the ceiling and side wall of the wind tunnel's working section to facilitate viewing as well as photography of flow patterns. A turntable, 0.21 m in diameter, on the floor of the working section allows the rotation of building model(s), and consequently the wind incident to the building model(s). The illuminator is easy to move and can be placed at different positions. A Pitot tube is located immediately upstream of the turntable to measure the flow speed, which can be adjusted in the range 0–9 m/s. An inclined manometer indicates the exact value of the wind speed. A honeycomb made of straws is installed at the tunnel entry to straighten the air flow. The flow in this suction tunnel is uniform across the section under a stable flow rate.

The facility is small in dimensions, with a total length of 3.96 m and a height of 0.84 m. However, some additional space is required for adjusting the damper, hanging the reservoir and installing the

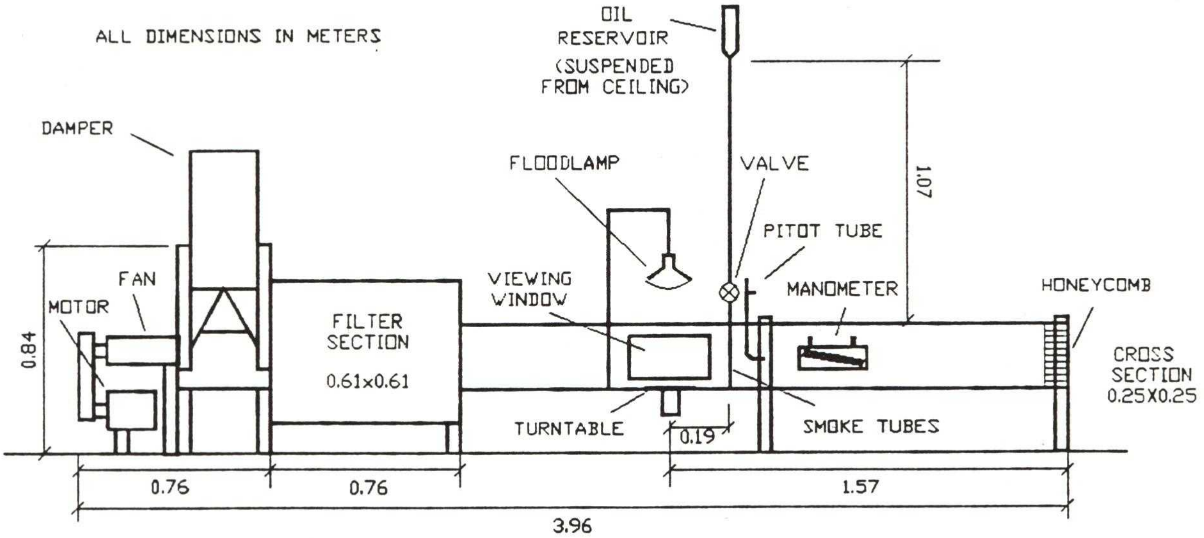

Fig. 1. Diagrammatic sketch of the wind tunnel facility and the smoke-generating system.

lamp(s). The entire system is shown in Fig. 2 set on a 1 m high table, which allows operators (students) to watch the wind flow comfortably from both viewing windows of the tunnel.

Using smoke in the wind tunnel is one of the most convenient approaches for visualizing the movement of air flows. In the current system, smoke is generated by feeding mineral oil through metering valves into heated stainless steel tubes. A 50 cm^3 oil reservoir is suspended from about 1 m above the wind tunnel to keep a certain pressure through the feeding tube. A horizontal and a vertical tube each made of 19 gauge hypodermic needle tubing are placed in the wind tunnel. There are seven holes on the vertical smoke tube and ten holes on the horizontal. All of the holes are about 0.7 mm in diameter and 12.7 mm apart from each other. A toggle switch allows the connection of either smoke tube to a Variac, which supplies power for heating. The oil evaporates and the resulting smoke exits through the tiny holes drilled into tube walls. Flow patterns around building models can be illuminated for the whole flow field or only in the plane of interest and recorded by a photo camera or a video camera.

It should be noted that a non-toxic oil is used for the test and the system has been located in a large and well-ventilated space in order to avoid potential problems to students' health. The visualization system was designed and fabricated by university personnel. Excluding the motor, which was donated by another laboratory, the total cost of materials, supplies and small equipment was less than $1000 (manometer, Variac, filters, plywood, etc.). However, the design and development of the system required a significant labour cost. Highly motivated personnel from our laboratory have devoted several weeks to this project.

FLOW CONSIDERATIONS

If the wind speed inside the tunnel is set at 4.5 m/s, the Reynolds number for a building model with a characteristic dimension of 5 cm will be 1.5×10^4. For a circular cylinder, such a Reynolds number is in the so-called subcritical range, which is much lower than that for full-scale buildings or structures encountered. Fortunately, most buildings in practice are designed with sharp edges so that the Reynolds number does not have such a significant influence on the flow separation as in the case of a circular cylinder. Therefore, basic flow phenomena could be simulated in this small tunnel despite the difference in Reynolds number. On the other hand, the size of the building model is restricted by the blockage effect the model may create in the flow. In this wind tunnel, a 5 cm cubic building contributes an area blockage of 4%, much lower than the generally accepted threshold of 10%, beyond which the wind flow inside the tunnel may be distorted due to the influence of the tunnel walls.

FLOW AROUND A BLUFF BODY

The basic principles and concepts related to the air flow around a bluff body are briefly reviewed in this chapter. The wind flow around a flat-roofed building is sketched in Fig. 3. The wind flow approaches perpendicularly to the building wall and forms a *vortex* in front of the building. The position on the building's windward face with a zero mean wind speed is referred to as the *stagnation point*. Flow *separates* at the front edge and may *reattach* on the building roof, depending upon both the building depth and characteristics of the oncoming flow. In the *shear layer* originating from

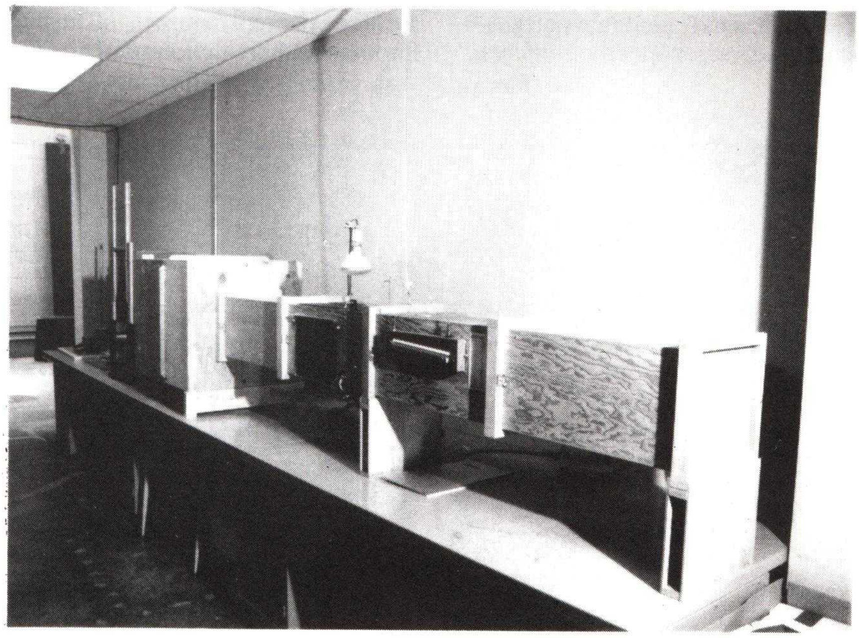

Fig. 2. Wind tunnel for flow visualization.

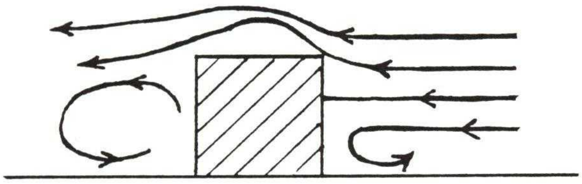

Fig. 3. Flow pattern around a flat-roofed building.

the *separation point*, *discrete vortices* may be generated due to strong *shear stresses*, and *shed* into the *wake* area behind the building, where wind flow circulates with relatively low speeds but high turbulence.

Basic principles of fluid mechanics can be recognized with the illustration of flow patterns around various building configurations. For instance, by the principle of conservation of mass, high wind speeds are expected in the area with denser streamlines, such as in the region above the shear layer in Fig. 3.

Bernoulli's equation assumes an elemental fluid particle having a constant momentum contributed by the static pressure and the inertial force (dynamic pressure) in a steady, potential flow. The wind pressure or suction on buildings can roughly be related to the wind speeds observed from the flow visualization. A more precise approach, like computerized image processing, can also be applied to derive the wind field, and the pressure distribution can be measured by analyzing the video records on an on-line computer.

Building models developed for the flow visualization are displayed in Fig. 4. Models are made of wood and covered in black paint. Wind flows around buildings with circular, rectangular and other cross-sections have been studied. Buildings with different roof slopes are also of interest when pressures or suctions on the building roofs are considered. Building groups may generate particular flow phenomena, such as channelling effects and downwash vortices, depending on building configurations. A more detailed description of flow patterns around buildings is given in the next section.

AIR FLOW VISUALIZATION AROUND BUILDING MODELS

To illustrate the application of the flow visualization facility, photographs of air flows have been taken for a number of building models. Wind speed was set at 4.5 m/s and Timax 400 (black and white) films were used with an exposure time of 1/125 s. Photographs for four groups of typical building models are presented and discussed in this section, along with the associated sketches of simplified flow patterns. These building models are cylinders with different cross-sections; buildings with different roof slopes; two rectangular buildings in a tandem position; and triangular buildings in pairs.

Cylinders with different cross-sections

Figure 5 shows the side view and the plan view of air flows around a circular and a square building. Wind flow separates about halfway around the circular cylinder, which creates a narrow wake, and thus a low drag force on the body. While the circular cylinder promotes lateral wind flows, the square cylinder obstructs the incident wind with its windward surface and induces strong flow separation at corners. Therefore, the windward surface is subject to high pressures, whereas high suctions occur on both side surfaces, especially on the edge close to the front corners. The stagnation point on the square cylinder is observed a little higher than that on the circular cylinder and this becomes a major cause for the strong vortex flow in front of the body. The flow separated from the top edge of the square cylinder is lifted well above the roof surface. The entrainment of turbulent shear flow imposes higher suction on the roof than that for a

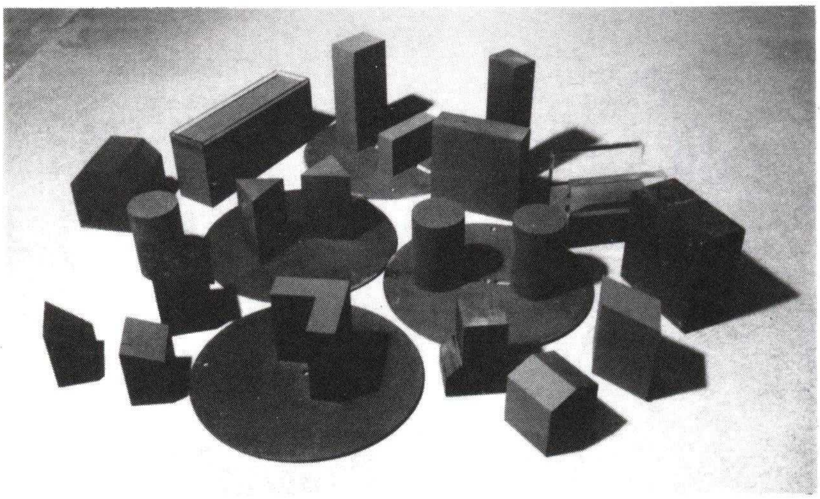

Fig. 4. Building models used for flow visualization.

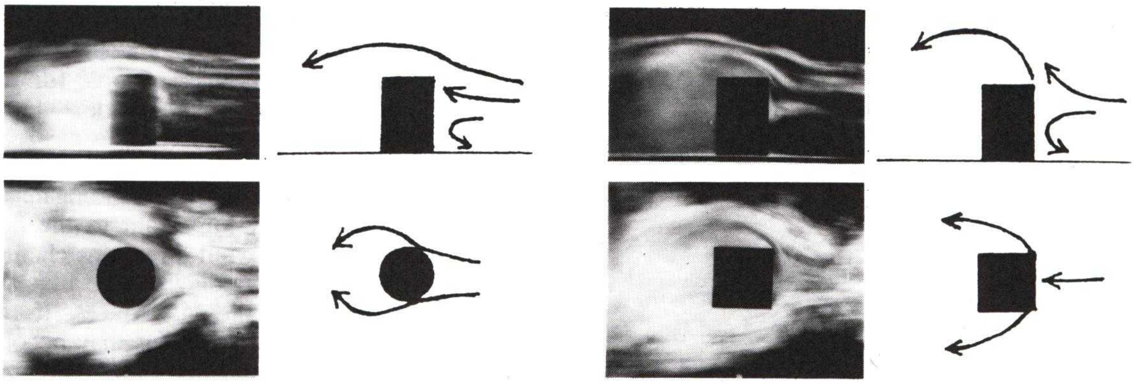

Fig. 5. Air flow around circular and square buildings.

circular building, where the separated flow moves closely to the roof surface following a smooth pattern.

Although not shown here, a square building with chamfered corners may also promote lateral flow, though to a lesser extent, and behave somewhat similarly to a circular building for certain wind directions. Chamfered corners can be considered as an effective remedy for reducing the wind force on the building and for lessening the wind disturbance for pedestrians. The effect of other than normal wind incidences for the square building can be examined and shown to the students. For instance, delta-shaped vortices are observed along the front edges of the building roof when an oblique wind flow approaches the building. These vortices cause extremely high suction on building roofs, as has been found by wind tunnel measurements.

Buildings with different roof slopes

Flow around two building models with the same ridge height but different roof slopes (22.5° and 45°) is visualized for two opposite wind directions as shown in Fig. 6. The flow pattern around a single-sloped building roof relates to the pressure or suction on the roof and can be explained as follows.

For buildings with a roof slope of 22.5°, wind flow smoothly attaches to the roof slope with no separation. The pressure coefficient on the roof is expected to have a low magnitude. For the opposite wind direction, the flow separates from the building ridge. The entrainment induced by the separated shear layer may cause high suction on the building roof. For the 45° roof, the wind flow impinges on the roof surface directly and creates positive pressure coefficients. If the wind comes from the opposite direction, the sharp ridge induces much stronger separation, and therefore higher suction than in the case of lower roof slope.

Other roof configurations—e.g. gabled roofs, stepped roofs, roofs with parapets or eaves—have also been developed and can show students the various features of the flow and the characteristic patterns due to the change in building geometry.

Two buildings in tandem position

A tall building may accompany a relatively low building on the other side of the street. Such building configurations may create different wind conditions at the pedestrian level depending on the heights and the distance between the buildings, as shown in Fig. 7. The model is designed with a changeable distance so that students can experiment themselves and find out the critical distance, which may induce the highest wind speed in the space between the two buildings, through the flow visualization.

For a small distance, the blockage effect of the front building is evident and no coherent vortex is formed between the two buildings. When the distance is increased, a large vortex, enhanced by the separated shear flow from the upstream building, brings the wind flow from a high level down to

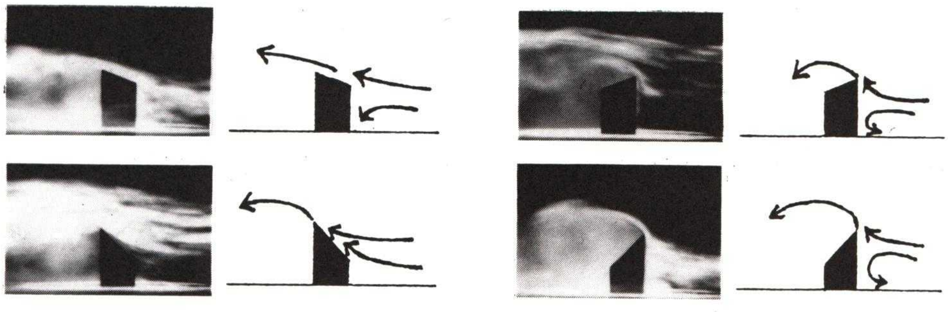

Fig. 6. Flow patterns around buildings with different roof slopes.

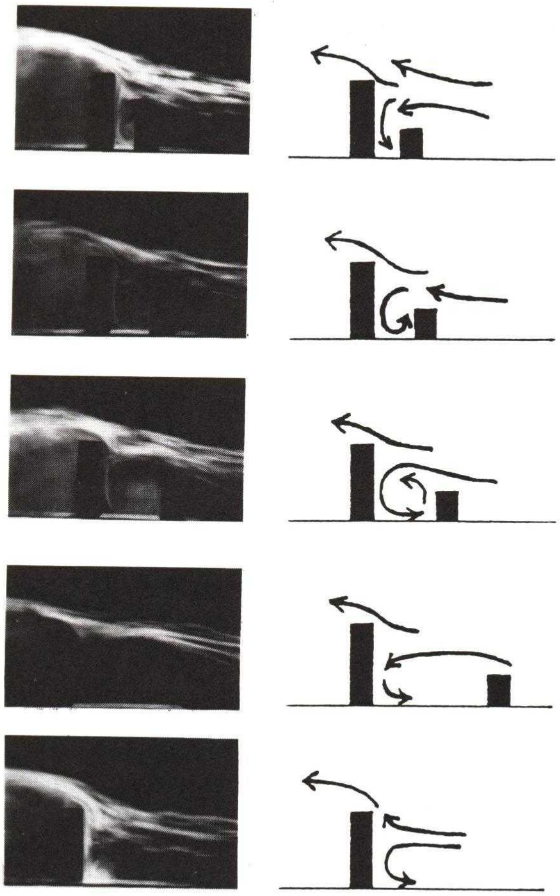

Fig. 7. Vortex flow between two buidings in tandem position.

the ground. With increasing distance, the large, stable vortex is replaced by the wake turbulence separated from the low building. A further increase of the distance reduces the influence of the front building and turns the two-building combination to an isolated building model as the distance approaches infinity. Note that the size of the front vortex, or the height of the stagnation point, has dominant influences on both the speed of the reverse flow at the ground level and the pressure distribution on the windward surface.

If wind flow comes along the gap between the two buildings, the so-called channelling effect prevails, as shown in the next example for two triangular buildings arranged side by side.

Triangular buildings in pairs

The unique shape of a triangular building makes the wind direction highly important to the flow pattern. The variation in wind directions changes the windward area of the building and the attacking angle of the wind to building surfaces. If two buildings are present, flow patterns may become more interesting and complicated as well. Figure 8 shows flow features for this arrangement.

With the largest surface area normal to the coming flow, as shown in the first picture in Fig. 8, both buildings provoke strong flow separation from their front corners and produce a wide turbulence region in the wake area. When the buildings face each other, flow separation still occurs around building corners. The wind flow is streamlined between the buildings and extrudes into the wake behind them. The venturi effect could be readily identified in the last two building models. Fast winds are expected in the gap region and the width of the wake flow of the last building model is clearly narrower than those of other arrangements. Flow instabilities are also seen in the last configuration—note the instantaneous asymmetry of the venturi effect there.

It is clear that what has been presented in this section is a small sample of the variety of flow features that can be visualized and experimentally tested by the students. The multitude of models shown in Fig. 4 provides an idea of the capabilities of this project and the potential benefit to the students in this area.

FINAL REMARKS

A small, low-cost wind tunnel with a flow visualization facility has been designed, developed and operated at the Centre for Building Studies. The suction tunnel has a square cross-section and a

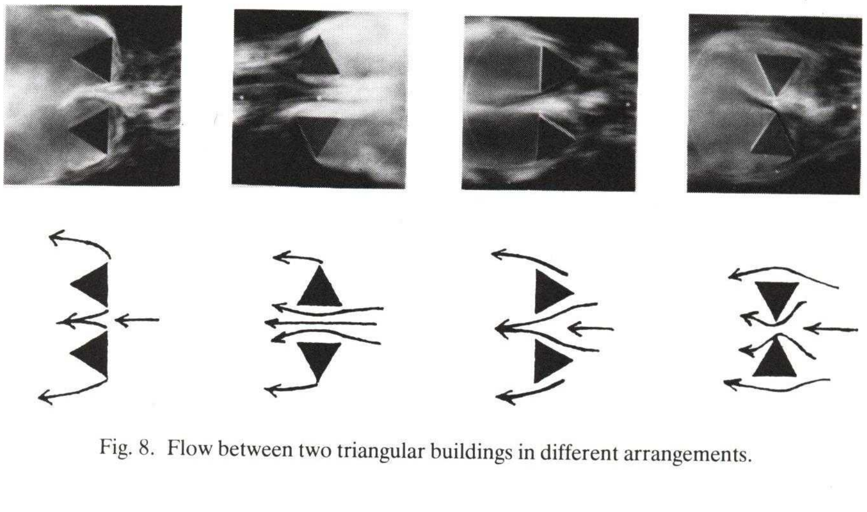

Fig. 8. Flow between two triangular buildings in different arrangements.

uniform wind speed distribution. The smoke can be generated by either a horizontal or a vertical smoke tube, depending on the flow features to be visualized. Photo and video cameras can be used to record flow patterns around different building models. From the demonstration of this facility, students get hands-on experience about wind flows around buildings. The performance of the system is satisfactory for teaching purposes and serves well the students' learning process.

Acknowledgements—The assistance and dedication of Mr Hans Obermeir of the Centre for Building Studies, who fabricated the tunnel and the flow visualization system, are highly appreciated.

Theodore Stathopoulos is Professor and Associate Director of the Centre for Building Studies and, more recently, Associate Dean of the Faculty of Engineering and Computer Science of Concordia University. He received his Civil Engineering Diploma from the National Technical University of Athens, Greece and both his M.E.Sc. and Ph.D. from the University of Western Ontario, Canada. His area of specialization is the evaluation of wind effects on buildings. He has published extensively and has obtained international recognition for his research. Dr Stathopoulos has also been active in the development of educational devices and models for the enhancement of teaching.

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