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The Design and Development of The FMRL 60x18 cm^2 Wide-Angle Screened-Diffuser Blower Tunnel
Part I: General Design Considerations

Alongkorn Pimpin and Asi Bunyajitradulya
Fluid Mechanics Research Laboratory, Department of Mechanical Engineering,
Faculty of Engineering, Chulalongkorn University,
Bangkok 10330, Thailand

Abstract

This is Part I of a series of three papers describing the design and development of the Fluid Mechanics Research Laboratory (FMRL) 60x18 cm^2 wide-angle screened-diffuser blower tunnel. The design and development stemmed from the need for a basic research facility - in this case, a wind tunnel - for the laboratory's planned fluid-dynamics research programs. Because wind tunnels are specialized research facility which must be designed and tailored for a particular flow of interest, and because the FMRL recognizes the ability to design and develop basic research facilities as the fundamentally important ingredient for conducting research, it decides to develop one. The developed tunnel proved to have quite satisfactory performance. It is then hoped that the design and development reported herein will be of value for fluid dynamics research community in Thailand.

In this first part, general design considerations regarding important configuration parameters such as test section shape and size, test section velocity, and type of wind tunnels are discussed. The considerations which are related to the design and development to meet local requirements are laid out, the result of which leads to the final design choice - the wide-angle screened-diffuser blower-type tunnel. The merits of the design, particularly its flexibility which makes it suitable for research laboratory in universities, are highlighted.

1. Introduction

Fluid mechanics is one of the research fields which are of vital importance to efficient use of energy and, as a consequence, to environment. Its importance lies on the fact that a major fraction of loss in engineering system is caused by fluid motion. In this regard, examples are

- combustion: fluid motion governs the mixing and combustion processes, hence, combustion efficiency;
- atmospheric vehicles (automobile, ship, aircraft, etc.): fluid motion causes drag, hence, reduction in propulsion efficiency;
- turbomachines and piping system: fluid motion causes friction, hence, loss of energy;
- air conditioning and ventilation: fluid motion governs the distribution of supply air, hence, the level of comfort;
- etc.

Not only in the area of energy that fluid mechanics plays such a vital role, it also plays important roles in vast majority of areas such as

- environment: fluid motion governs the dispersion and the distribution of pollutants;
- structural design: fluid motion causes aero/hydrodynamic forces on mechanical and civil structures;
- electronics: fluid motion governs heat transfer rate from dissipative circuits;
- biomedical: fluid motion governs blood and air circulations; thus, the study has its application in the design of artificial heart, heart valve, heart-lung machine, breathing aids, etc.;
- etc.

As is indicated by the amount of literatures in the last two decades, the recent trend in fluid mechanics research lies not only on the striving towards better understanding of the physics of fluid motion but also on the manipulation and control of the motion so that certain desired effects can be achieved. See, for example, Lumley et al. (1996), and Gad-el-Hak et al. (1998).

Realizing the importance of research in the field of fluid mechanics, the Fluid Mechanics Research Laboratory (FMRL) of the Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University has as its policy the research in fluid dynamics and flow control and as its goal the expertise in some of the areas in this field. To achieve this goal, its members have adopted the do-it-ourselves approach for the making of some of the basic research facility and instrumentation. This series of three papers reports the design and development of the FMRL 60x18 cm^2 wide-angle screened-diffuser blower tunnel which was designed and built locally and which will be used for various research projects in the laboratory. Part I concerns with the general design considerations that lead to the type and the parameters of the wind tunnel chose to build - a 60x18 cm^2 wide-angle screened-diffuser blower tunnel - and with the general description of the tunnel. Part II concerns with the performance of the wide-angle screened-diffuser which is the crucial component for a wind tunnel of this type. Part III concerns with the flow conditioning section, i.e., the settling chamber, the contraction, and the calibration of the tunnel.

Finally and firstly, it should be noted that this series of papers is not intended to be an extensive review in or an elementary overview of wind tunnel design. But, rather, it is intended to be a guideline to some of the practical aspects of the design of a wind tunnel. In addition, it focuses mainly on the type of the wind tunnel chosen, i.e., the wide-angle screened-diffuser blower type. Nonetheless, some comparisons are made with other types, at least as far as the local key factors influencing the final design choice are concerned. These key factors are not, however, expected to be much different (with some exceptions, of course) here at Chulalongkorn University than any other organizations in Thailand. Secondly, the authors dare not claim that their tunnel is superior to many of the excellent tunnel being used today. Nonetheless, its performance is quite satisfactory for many of the research projects being planned for it. In addition, the design and the resulting tunnel have the following merits.

- the flexibility of the tunnel in accommodating various flow configurations makes it suitable for fluid dynamics research at university-scale laboratory, taking the cost and the economics into consideration,
- the materials used in the construction of the tunnel can be found locally, and
- the design and the construction are quite simple that it can be done in universities.

It is then hoped that this series of papers will be of value to the readers who are interested in developing a wind tunnel.

For further details on wind tunnels and their designs, the reader is suggested to the works of, for example, Bradshaw and Pankhurst (1964), Mehta (1977), and Rae and Pope (1984).

2. Wind tunnel

Wind tunnel is a basic research-facility for studying of fluid motion. It is used for supplying flow with desired, or *standard*, condition - which is almost always steady, uniform, with low freestream-turbulence level - to the test section. In the test section, the flow configuration which is to be investigated is mounted.

At the heart of any experiment, controlled environment and *a set of specified experimental conditions* need to be established. A study of fluid motion using wind tunnel is no exception. That is, in the test section a desired flow configuration with *the corresponding set of flow conditions* needs to be established. It is important to point out that the corresponding set of flow conditions referred to here is not the same as the standard condition. The former depends on the flow configuration to be investigated and usually varies from one configuration to another, while the latter, as mentioned above, almost always refers to steady, uniform, with low freestream turbulence level. Since most of the study on external flows require a steady, uniform freestream with low turbulence level, the standard condition may be considered as part of the corresponding set of flow conditions. This point will be further elaborated in the next section.

There are many types of wind tunnel available. They are categorized broadly but not exclusively as

- subsonic/supersonic speed,
- open/closed test section,
- open/closed return, and
- suction/blower type.

This paper focuses on a low subsonic-speed, closed test-section wind tunnel which is commonly employed in low-speed fluid dynamics research.

2.1. Performance indices

The desired standard flow condition supplied to the test section is almost always steady, uniform, with low freestream-turbulence level. Hence, the three important parameters used for the determination of the quality of a wind tunnel are the uniformity of the mean flow, which is associated with the spatial distribution of freestream velocity; the steadiness of the mean flow, which is associated with low-frequency fluctuation of freestream velocity; and the freestream-turbulence level, which is associated with high-frequency fluctuation of freestream velocity.

Non-uniformity of the freestream velocity in the test section is usually caused by poor quality flow-conditioning devices in the settling chamber or a contraction with low contraction ratio. It is indicated in terms of the distribution of total pressure or of mean velocity at the contraction exit. Unsteadiness of the freestream velocity in the test section is usually caused by large-scale separation in the upstream components such as a diffuser. It is indicated in terms of the amplitude of low-frequency fluctuation in freestream velocity at the contraction exit. High freestream-turbulence level is usually caused by a contraction with low contraction ratio and/or poor quality flow-conditioning devices in the settling chamber. It is indicated in terms of turbulence intensity at the contraction exit.

In addition to these three qualities, the thickness, and the uniformity of the distribution of the thickness, of the boundary layer, and the uniformity of the distribution of the skin friction coefficient across the contraction exit may be of vital importance in some research areas such as laminar-to-turbulent transition.

Efficiency of a wind tunnel is measured in terms of the energy ratio *ER*, defined as the ratio of the kinetic energy of the airstream in the test section to the input energy at the fan (Rae and Pope, 1984).

2.2. Configuration parameters

In this subsection we shall briefly describe the configuration and the important configuration parameters for wind tunnels. For more detailed discussion of these configuration parameters pertaining to various aspects of the design, we shall postpone to the next section. For broader and more general discussion of these parameters, the reader is referred to, for example, Rae and Pope (1984).

The main components of low-speed wind tunnels are driving fan, diffusers, settling chamber, contraction, and test section. The driving fan is necessary for generating flow at a desired speed through the wind tunnel. For a closed-return tunnel, the power input at the fan is spent in overcoming friction in the tunnel, while for an open-return tunnel, additional power is required to accelerate atmospheric air from rest to the desired speed in the test section. To be able to study a wide range of fluid motion, it is desirable to have a wind tunnel with the maximum test section velocity as high as possible. At the same time, since loss in each component of a wind tunnel is proportional to the square of the flow speed through that component, it is also desirable to keep the flow speed to a minimum in all other parts of the tunnel. Therefore, diffusers are often necessary to reduce the flow speed through all other components. Diffusers reduce flow speed by expanding the flow area. They are parameterized by their area ratio AR, defined as the ratio of an exit area to an inlet area. Depending upon the type of a wind tunnel, the number and the locations of diffusers vary. Since various components of a wind tunnel often generate large-scale turbulence and non-uniformity in the flow, a settling chamber is required for conditioning the flow, i.e., removing turbulence and non-uniformity. After the flow is conditioned in the settling chamber, it is accelerated through a contraction to a desired speed in the test section. In contrast to a diffuser, a contraction accelerates flow speed by contracting the flow area. Thus, a contraction is parameterized by its area ratio called *contraction ratio c*, defined as the ratio of an inlet area to an exit area. In addition, a contraction also helps reducing non-uniformity of freestream velocity and freestream turbulence. Test section is the part of a wind tunnel where the flow configuration is installed and measurements are made. The settling chamber, the contraction, and the test section are often located in that order in the downstream direction of a wind tunnel.

The most important configuration parameters for wind tunnels are

1. test section shape and size,
2. test section maximum velocity,

and, to a lesser extent,

3. type (open/closed return, suction/blower tunnel),
4. contraction ratio, and
5. settling chamber shape and size.

Table 1 gives examples of these parameters from various studies.

3. General design considerations

The first question one needs to ask before making any decision regarding test section shape and size, test section maximum velocity, type of the wind tunnel, etc., is "what type of flow will be studied in this tunnel?" The answer to this question will dictate the values of the configuration parameters mentioned in the last section.

In real life, however, the following factors, more often than not, also have strong influence on the final values of these parameters:

- space available (room length x height x width),
- costs.

Test section shape and size

It cannot be overemphasized that test section shape and size are dictated by the flow configuration to be investigated and, accordingly, by the corresponding set of specified experimental conditions required. For simplicity, in this paper we shall limit our discussion to only test sections of rectangular cross section. We shall designate the streamwise coordinate as x, traverse as y, and spanwise as z. Hence, the three dimensions of the test section are its width (W, measured along z), height (H, measured along y), and length (L, measured along x). As long as the required set of flow conditions in the test section can be established without interference from the walls, the test section of a chosen size is satisfactory. Hence, it is more meaningful to discuss the size of a test section in terms of the minimum value required of its three dimensions for a particular type of flow to be investigated. (A test section of a larger size can always be chosen, at the expense of a higher cost.) In this regard, some examples are in order.

For a study of a nominally two-dimensional turbulent boundary layer in constant pressure using a tripped boundary layer on the tunnel floor – which is much thicker than the untripped boundary layer on the tunnel ceiling - the condition of two-dimensionality of the boundary layer needs to be established; such a tunnel is usually called a *boundary-layer tunnel.* To achieve this without any special form of boundary layer control and at least as far as the size of the test section is concerned, the width of the test section should be sized according to the boundary layer thickness, δ, at the measurement location. For example, Muck et al. (1985), see also Hoffman et al. (1985), used a boundary layer tunnel with W/δ greater than 20 in their studies of the effect of convex curvature on turbulent boundary layers; and Westphal et al. (1987) used equal value in their study of the vortex/boundary-layer interaction.

On the other hand, the height of the test section depends on interference from the tunnel ceiling. In this regard, H/δ of 5 is considered to be adequate, see Muck et al. and Westphal et al. Another related factors which are equally important are the blockage effect and the desired static pressure distribution. The blockage effect decreases as H/δ increases. Therefore, for a constant boundary layer experiment, a larger H/δ is desirable.

Nonetheless, Muck et al. made no attempt to eliminate the blockage for the reasons given in the cited reference, see also Smits et al. (1979), while Westphal et al. used an adjustable wall to eliminate the blockage and to create a desired static pressure distribution.

Therefore, most of boundary layer tunnels – with no special scheme for boundary layer control applied - have a rectangular test section with larger width and smaller height: W/δ, of at least 20 and H/δ of at least 5. On the other hand, some scheme for boundary layer control may be applied and the test section may have different W/δ and H/δ values; see, for example, Cluaser (1954), and Simpson et al. (1981).

The length of the test section - measured from contraction exit to the next downstream component - is determined mainly by two factors: the furthest downstream location at which the measurement will be made, and the possibility of interference from upstream effects of the downstream components at that location. Therefore, the total length of the test section must be at least equal to the sum of the two lengths determined by each factor. Since most flows evolve downstream through various states (e.g., from developing to fully-developed), and each state occupies certain downstream distance, the first of these two factors therefore depends on the state of the flow at which the study is targeted. In the case of a fully-developed turbulent boundary layer in constant pressure, most of the effects of perturbations disappear in 30-40 boundary-layer thicknesses (Bradshaw and Ferriss, 1968). Thus, the downstream distance of at least 40δ from a trip wire is required if the measurement is to be made of the flow in a fully-developed state. Muck et al. employed approximately 65δ; Westphal et al., 57δ. For other types of shear flows, the reader is referred to, for example, Bradshaw (1966), Hussain and Zedan (1978), Husain and Hussain (1979), and Smits and Wood (1985). The second factor depends primarily on the downstream component. The downstream component, in turn, depends on the type of the tunnel. For an open-circuit blower tunnel, the flow from the test section is discharged to atmosphere either directly as a free jet or through a diffuser. For a closed circuit tunnel, the downstream component is usually a diffuser. In both cases, the distance of twice the hydraulic diameter of the test section is often adequate.

As another example from another type of flow, a jet in crossflow is a highly complex three-dimensional flow. The extent of the flow grows in both y- and z-directions as the flow evolves downstream. It was found that the trajectory and the physical dimension of the jet depend on the diameter of the jet, d, and the effective velocity ratio, r. The effective velocity ratio is defined as the square root of the momentum-flux ratio,

$$r = \sqrt{\frac{\rho_j U_j^2}{\rho_{cf} U_{cf}^2}},$$

where ρ is density, U is velocity, and subscripts j and cf refer to jet properties and crossflow properties respectively. Specifically, the centerline trajectories of jets of different r were found to correlate well with the rd-scale according to the correlation

$$\frac{y}{rd} = A\left(\frac{x}{rd}\right)^m,$$

where the origin of the coordinates in this case is at the jet exit, and A and m are constants (Smith and Mungal, 1998; Pratte and Baines, 1967). Thus, the test section for an experiment in jets in crossflow should be sized with the above relation taken into consideration. Smith and Mungal used a square test section with minimum $W/d = H/d = 54$ and $L/d = 94$ ($W/H = 1$); Moussa et al. (1977) used a rectangular test section with $W/d = 24$, $H/d = 48$, and $L/d = 236$ ($W/H = 0.5$); and Mchamon et al. (1971) used a circular test section with the jet flushed on a flat plate at the bottom with $W/d = 54$ (W measured at the center), and $H/d = 21$ (H measured from floor to the center, $W/H = 2.6$).

Finally, another two related factors can also and often do influence the minimum size of the test section. These two factors are the required spatial resolution of the measurements and the diagnostic tool employed, e.g., pressure probe, hot-wire anemometer, laser-doppler velocimeter, particle-image velocimeter, etc. To achieve a required spatial resolution, the flow configuration may have to be larger (e.g., thicker boundary layer, larger jet diameter) or the spatial resolution of the diagnostic tool may have to be better. The former approach in getting the required resolution affects the minimum size of the test section directly. Yet another practical aspect, to get a desired spatial resolution, some part of the diagnostic tool, e.g., probe and traverse, may have to be put inside the test section. This obviously can disturb the flow if the test section is too small.

Test section velocity

The flow configuration and the corresponding set of specified experimental conditions also dictate the test section velocity. Generally, the dominant parameter in the case of a low-speed fluid motion is the characteristic Reynolds number of the flow, defined as $Re=UL/\nu$, where U is the characteristic velocity, L is the characteristic length, and ν is the kinematic viscosity. Since the characteristic velocity of the flow is related to and is often equal to the test section velocity, the latter can be determined from the former.

Type of wind tunnels

With narrower class of wind tunnels in mind, i.e., a low-subsonic speed, closed test-section tunnel, the choice for the type of the tunnel is reduced to either an open- or a closed-return and either a suction- or a blower-type tunnel.

For the same test section shape and size, the same test section maximum velocity, and the same contraction ratio, the choice between an open return and a closed return is mostly influenced by

- space available,
- cost of materials and construction,
- flexibility in accommodating various flow configurations,
- ability to control flow quality,
- energy consumption, and
- noise.

A closed-return tunnel generally requires more space than an open-return tunnel owing to the need for the installation of the return path. Given that the test section and the return path are mounted horizontally, the width of space required for a closed-return tunnel is approximately at least 2.5-3 times that of an open-return tunnel. Moreover, owing to additional components associated with the return path, e.g., corners, corner vanes, return diffuser, the cost of materials and construction of a closed-return tunnel is usually higher by an approximate factor of 1.5 to 2, excluding the cost of the driving fan.

The most important advantage of an open-return tunnel (a blower type in particular) over a closed-return one, especially for a wind tunnel of small to moderate size that is often used for research in universities, is its flexibility. Due to the open-ended architecture of an open-return tunnel, it has more flexibility in accommodating many different test sections for many flow configurations. For example, for a wide-angle screened-diffuser blower tunnel, the important components of the tunnel are, in the order from upstream to downstream: blower, flexible duct, settling duct, wide-angle screened-diffuser, settling chamber, contraction, and test section. In this respect, the modification needed to accommodate various test sections can be considered as two cases according to the changes needed to be made to the existing tunnel:

Case 1: If the new test section for a new flow configuration has an inlet of the same size as that of the existing one, only the new test section needs to be made and installed in place of the existing one. All other existing upstream components, i.e., blower, flexible duct, settling duct, screened-diffuser, settling chamber, and contraction, can still be used. This is provided that the test section maximum velocity and the contraction ratio are acceptable for the new flow configuration.

Case 2: If the new test section for a new flow configuration has an inlet of different size from that of the existing one, only a new contraction and the new test section need to be made and installed in place of the existing ones. All other existing upstream components, i.e., blower, flexible duct, settling duct, screened-diffuser, and settling chamber, can still be used. This is provided that the test section velocity and the contraction ratio associated with the new test-section/contraction are acceptable for the flow configuration.

Therefore, from the consideration for flexibility it is desirable to have a settling chamber as large as possible to accommodate a wider range of test section sizes (especially towards the larger size) and the corresponding contraction ratios. Similar consideration is applied to the blower and its operating range.

On the other hand, it may be easier to control the flow quality in the test section of a closed-return tunnel than of an open-return one. This is due to the fact that an open-return tunnel draws air directly from the room. Therefore, the flow through the tunnel depends on the flow pattern in the room. This is particularly true for a suction-type tunnel that does not have an appropriate flow conditioner, i.e., a settling chamber, upstream of the test section. In this case, the flow pattern in the room and the ratio of the room volume to the volume flowrate through the tunnel should be considered; the larger, the better. In any case, this is not in itself a serious drawback as long as an appropriate settling chamber is installed upstream of the test section.

However, one drawback associated with a suction-type tunnel and this settling-chamber remedy should be pointed out. Since static pressure inside the test section of a suction-type tunnel, with a settling chamber or not, is always lower than atmospheric pressure (room air is drawn directly into the test section without passing first through a fan), leakage into the tunnel is a potential problem. This problem is amplified when a settling chamber is employed upstream of the test section owing to considerable pressure drop associated with the settling chamber, thus, making the test section pressure even lower. This problem is yet further amplified by the fact that, the more the flow needs to be conditioned, the larger the pressure drop is required (see Part III), and the lower the pressure in the test section becomes.

For a blower-type tunnel, on the contrary, the flow passes through a blower first before entering the test section. Therefore, the problem of controlling the flow quality and its consequence associated with a suction-type tunnel just described, in some way, is not encountered for two reasons. Firstly, because the flow at the exit of the blower is generally much more turbulent compared with the irregular flow pattern in a room at the suction-side of a suction tunnel or of the blower, the flow inherently needs to be conditioned rather heavily. The required flow-conditioning scheme for the exit flow from the blower is usually sufficient for this inlet irregularity. As a consequence of the more elaborated flow-conditioning scheme required, the flow quality is better controlled than a suction-type tunnel, at the expense of higher loss and higher energy consumption. Secondly, because the static pressure inside the test section of a blower-type tunnel is higher than the atmospheric pressure, leakage occurs in the opposite direction, i.e., out of the test section.

When comparing energy consumption, a well-designed closed-return tunnel usually consumes less energy than an open-return one. This is because of the energy waste associated with the kinetic energy of the free jet at the exit of an open-return tunnel. To achieve an even better energy ratio for a closed-return tunnel, a diffuser just downstream of a test section is often required to reduce the flow speed to a minimum before it enters the first corner. Certainly, this improvement in energy ratio is achieved at the expense of an additional space required for the tunnel and the increase in cost of construction.

Finally, an open-return tunnel often generates more noise than a closed-return one. Specifically, for a wide-angle screened-diffuser blower tunnel the three main sources of noise are the blower, the diffuser, and the free-jet at the exit of the test section.

Contraction ratio

A contraction is used for accelerating air from the settling chamber to the test section. Another effects of a contraction are to reduce mean velocity variation and to reduce freestream turbulence intensity. For further details on these aspects of a contraction, see Part III, Batchelor (1953), and Uberoi (1956). It suffices to mention here that, for an axisymmetric contraction with a contraction ratio of c, the factors of reduction of *percentage* mean velocity variation in the streamwise direction, μ, are given by

$$\mu = \frac{1}{c^2}, \qquad (1)$$

and in the cross-stream direction, ν, by

$$\nu = \frac{1}{\sqrt{c}}, \qquad (2)$$

and the factors of reduction in turbulence intensity in the streamwise direction, μ', are given by

$$\mu' = \frac{\sqrt{\overline{u_2'^2}}/U_2}{\sqrt{\overline{u_1'^2}}/U_1} = \frac{1}{2c^2}\sqrt{3\left(\ln(4c^3)-1\right)}. \qquad (3)$$

and in the cross-stream direction, ν', by

$$\nu' = \frac{\sqrt{\overline{v_2'^2}+\overline{w_2'^2}}/U_2}{\sqrt{\overline{v_1'^2}+\overline{w_1'^2}}/U_1} = \frac{1}{2}\sqrt{\frac{3}{c}}, \qquad (4)$$

where u', v', w' are the velocity fluctuations in the streamwise, traverse, and spanwise directions; and subscripts 1 and 2 refer to the contraction inlet and exit, respectively (Batchelor, 1953). Typically, the contraction ratios of 7-11 are used. The factors of reduction of percentage mean velocity variation and of the turbulence intensity are then

for $c = 7$: 0.020, 0.38, 0.044, and 0.33;
for $c = 9$: 0.012, 0.33, 0.028, and 0.29;
for $c = 11$: 0.008, 0.30, 0.020, and 0.26;

respectively. Larger contraction ratio, however, requires larger settling chamber and, hence, larger space for the same test-section size.

If possible, though not strictly necessary, the aspect ratio of the flow cross section along the contraction, from inlet to exit, should be kept constant. Further discussion of contractions and their design is given in Part III.

Settling chamber shape and size

As mentioned earlier, from the consideration for flexibility it is desirable to have a settling chamber as large as possible to accommodate a wider range of test-section sizes. This certainly requires a room of considerable height.

4. Background and general requirements/considerations for the FMRL wind tunnel

To facilitate various research projects in the FMRL, the decision to build a wind tunnel was made. Some of the requirements/considerations and their solutions are as follows.

- **Flexibility:** From an economics consideration, at the outset we decided that the tunnel must be able to accommodate as many research projects as possible. Hence, flexibility of the tunnel was our first and foremost priority. The tunnel must be easily modified to accommodate many different test sections of various sizes, with the least cost of modification.
- **Planned research programs:** Since many of fluid dynamics researches, particularly those related to three-dimensional external flows for which we target, require large test section, it was therefore desirable to have a wind tunnel which could accommodate a test section of an equivalent area of at least 90 x 90 cm^2 (WxH) and a maximum test section velocity of approximately 25 m/s.
- **Utilization of space:** The tunnel was going to be located in Room 316, Engineering V building. The room size was 12 x 15 x 3.9 m^3 (WxLxH). However, because of other research facilities, not all of the space in this room was planned for this tunnel. The maximum space that could be used was 6 x 15 x 3.9 m^3.
- **Costs and resources:** Limited and scattered resources were available.

⇒ From flexibility, space, and total cost considerations, and with the targeted test-section size in mind, we decided that an open-return tunnel was more suitable for us than a closed-return one for the reasons given in the last section. The choice was then reduced to a blower type or a suction type. From the control of flow quality consideration, we chose a blower type for the reasons also given in the last section. In addition, a blower-type tunnel is more flexible than a suction-type tunnel in that the connection between the test section and the fan of the latter needs to be changed if the size of the test section is changed. Hence, we chose an open-return blower-type tunnel for its merits of flexibility in accommodating test sections of various sizes. And, in this sense, a settling chamber size was our main focus in the design process and was chosen to be one of the parameters describing wind tunnel configuration.

⇒ Once we decided on an open-return blower-type tunnel, initially, again from flexibility consideration we wish to build a tunnel with the settling chamber as large as possible. In our case, the room height allowed for a settling chamber of inner height as high as 2.7 m and the space width comfortably allowed for an additional 2.7 m in inner width. This could accommodate the original targeted test section of 90x90 cm^2 with a comfortable contraction ratio of 9. Due to limited resources, however, the original goal was unattainable and we settled for a smaller settling chamber.

⇒ Since we had also a plan for a study on the effects of vortex-generator configurations on different flow regimes of diffusers, which required a wind tunnel with the test section of 60 cm in width and 18 cm in height (the test section in this case is just a leading duct to the diffuser) and the desired maximum test-section velocity of 25 m/s, we carried on the original design concept of maximizing the settling chamber size to the new tunnel. From the resources available as well as from the consideration for an appropriate contraction ratio, we chose the settling chamber size of 1x1 m^2, which gave a contraction ratio of 9.3.

⇒ The square settling chamber was chosen because it maximized the use of vertical space (room height) and minimized the width of the tunnel while at the same time still kept the rectangular test section oriented in a conventional manner. Conventionally, but not always, it is desirable to have a rectangular test section with the major axis - the longer side - lie horizontally and the minor axis - the shorter side - lie vertically. The reason, in part, stems from the fact that, it is more convenient to mount a traverse for a measurement probe on the top of the test section and to have the probe traverse in the vertical direction. This orientation prevents the traverse and the probe from being excessively too high. On the other hand, if a rectangular settling chamber was to be used with the major axis lie vertically to minimize the width of the tunnel, the major axis of the test section had to lie vertically also. This was to prevent the switching of the orientation of the major axis of the flow cross-section as the flow went through the contraction.

- **Materials and equipment:** From the local fund that we had, we decided that local resources must be utilized to the fullest and that local materials must be used.

⇒ Therefore, an existing set of a 15-inch backward-curved centrifugal blower with 3-hp motor and a 2.2-kW variable frequency inverter was used. It was then not expected that the desired maximum test-section velocity of 25 m/s could be achieved. Nonetheless, the preliminary test of the blower and the estimation of loss in the tunnel indicated that it was sufficient for our application at hand, i.e., it could drive the tunnel to the test section velocity of 10-15 m/s.

- **Design and construction:** The tunnel must be easy to construct and assembled by local students. It must have a modular design and could be disassembled into sections for ease of relocation. It must have high mobility to be moved around the room when necessary. Due to commonly long hours of testing, the tunnel must be easy and comfortable to work with.

⇒ The tunnel was made of wood. Each section, i.e., blower, screened-diffuser, settling chamber, contraction, and test section, had its own wheeled-support and was connected to one another by flanges.

⇒ From flexibility and economics viewpoint, the contraction support could accommodate contraction of various exit sizes, matched to the corresponding test-section inlet.

⇒ The wind tunnel centerline was at a comfortable working height, 130 cm from the floor.

5. General description of the FMRL wind tunnel

Figures 1 and 2 show the schematic and the photograph of the FMRL 60x18 cm^2 wind tunnel. The tunnel is located in the Fluid Mechanics Research Laboratory (FMRL), Room 316, Engineering V building, Faculty of Engineering, Chulalongkorn University. It is a wide-angle screened-diffuser blower tunnel. The main components, from upstream to downstream, are a filter or safety guard, a centrifugal blower, a flexible duct, a settling duct, a screened-diffuser, a settling chamber, a contraction, and a test section.

The blower is used for supplying air through the tunnel. It is a 15-inch backward-curved centrifugal blower which is driven by a 3-hp motor and a 2.2-kW variable frequency inverter. It has a conventional bell-shaped inlet with the nominal inlet diameter (flange diameter) of 15.75 inches and a rectangular exit of 11.5 x 16 in^2 (WxH). It is a bottom-horizontal discharge type. Two overlaid screens of mesh 16 and 2.5 (wire diameters of 0.24 and 0.66 mm respectively; mesh 16 is a household screen) are installed at the inlet of the blower as a safety guard and a protection for screens in the settling chamber.

It should be pointed out that, generally, if a hot-wire anemometer is to be used as a diagnostic tool in the test section, an air filter should be installed at an inlet of the blower. This is due to the fact that hot-wire sensors are very fragile and easily broken when hit by dust particle of considerable size.

The flexible duct, 24 cm long, is used for connecting an exit of the blower (11.5 x 16 in^2) to the inlet of the settling duct (45 x 45 cm^2) as well as for isolating vibration from the blower to the rest of the tunnel. It is made of rubber sheet sewed at the edges to form the shape of an expansion duct. At both ends of the duct, flanges made of aluminum angle are attached.

The settling duct is used for conditioning the flow before it enters the diffuser by allowing the flow from the exit of the blower to settle and the boundary layers to re-attach. This is necessary since the flow coming out of the blower is highly turbulent with strong swirling component. (However, Mehta, 1977, suggested that swirling flow from the blower might help delaying separation in the diffuser, hence, was of benefit.) The settling duct has a square cross-section and dimensions of 45x45x60 cm^3. It is made of 15-mm thick plywood and aluminum angles. Two overlaid screens of mesh 16 and 2.5 are installed at the inlet to help conditioning the flow as mentioned above. In addition, a screen of mesh 2.5 is installed at the exit.

The diffuser is used for decelerating the flow to minimal speed before it enters the settling chamber. This helps reducing the loss in the settling chamber where the flow is conditioned with a honeycomb and screens. (Losses through honeycomb and screen are proportional to the square of the throughflow speed.) It is a symmetric wide-angle screened-diffuser with an area ratio of 5 and an equivalent included angle of 26 degrees. It has an inlet area of 45x45 cm^2, an exit area of 100x100 cm^2, and length of 120 cm measured along the axis. It is made of 15-mm thick plywood. Four screens of mesh 8 (wire diameter of 0.5 mm) are installed at the locations 28, 48, 68, and 88 cm from the inlet (measured along the axis). Note that at the exit of the settling duct, or at the inlet of the diffuser, one screen of mesh 2.5 is already installed. For further details of the diffuser and its performance, see Part II.

The settling chamber is used for conditioning the flow so that variation in mean velocity as well as turbulence intensity in the freestream can be reduced to a minimal. The removal is achieved through the actions of honeycomb and a series of screens. This is necessary since the exit flow from a diffuser is generally non-uniform and highly turbulent. The settling chamber has a cross section area of 100x100 cm^2 and length of 134 cm. Flow conditioning devices in the settling chamber consist of, from upstream to downstream, a screen of mesh 4 (wire diameter of 0.6 mm); a honeycomb made of sections of PVC pipe (15 mm in inner diameter, 1 mm thick, and 125 mm long) sandwiched between two mesh 4 screens; and a series of seven mesh-16 screens. For further details of the settling chamber, see Part III.

The contraction is used for accelerating the flow from the settling chamber to the test-section velocity at the contraction exit. It also helps removing variation in mean velocity as well as turbulence intensity in the freestream. It has an inlet area of 100x100 cm^2 nominal (102x102 cm^2 actual), an exit area of 60x18 cm^2 (WxH), and a length of 150 cm nominal (170 cm actual), giving a contraction ratio of 9.3. The wall contours are designed with fourth-degree polynomials and with the inflection point located at 2/3 distance from the inlet. This is to accommodate two boundary conditions at each end (position and zero-slope) and the specified location of an inflection point. For further details of the contraction, see Part III. It is made of four steel plates of 2.5 mm in thickness.

6. Other considerations

Considerations for loss and space

In the design process, the total energy loss through the tunnel must be calculated to determine the required blower size. Generally, for a wide-angle screened-diffuser blower tunnel, energy loss, h_l, in each component, say component i, of the tunnel can be expressed as

$$h_{li} = K_i' \frac{V_i'^2}{2}, \quad (5)$$

where K_i' and V_i' are the loss coefficient of and the average flow speed through component i respectively. It is however more useful to express this as an equivalent loss, defined with respect to the test section velocity V_T as

$$h_{li} = K_i \frac{V_T^2}{2}, \quad (6)$$

where K_i is the equivalent loss coefficient.
Hence,

$$K_i = \left(\frac{V_i'}{V_T}\right)^2 K_i' = \left(\frac{A_T}{A_i}\right)^2 K_i', \quad (7)$$

where A_T is the test section area, and A_i is the flow area of component i, usually taken as an inlet area.

From energy consideration, see for example Fox and McDonald (1978), the static-pressure rise Δp measured across the blower can be calculated from

$$\frac{\Delta p}{\rho_{air}} = \left(\sum_i K_i\right)\frac{V_T^2}{2} + \left\{\alpha_{BI}\left(\frac{A_T}{A_{BI}}\right)^2 - \alpha_{BE}\left(\frac{A_T}{A_{BE}}\right)^2\right\}\frac{V_T^2}{2} \quad (8)$$

where $\sum_i K_i$ is the sum of equivalent loss coefficient of all components,

$$\sum_i K_i = (K_F + K_{FD} + K_{SD} + K_{DS} + K_{SC} + K_C + K_T + K_J) \quad (9)$$

and subscripts F, FD, SD, DS, SC, C, T, and J refer to the filter, flexible duct, settling duct, screened-diffuser, settling chamber, contraction, test section, and exit jet, respectively; ρ_{air} is the density of air; α_{BI} and α_{BE} are the kinetic energy coefficients, and A_{BI} and A_{BE} are the flow areas, at the blower inlet and exit, respectively. For all practical purpose, α_{BI} and $\alpha_{BE} \sim 1$.

Because loss in each component is proportional to the square of the throughflow speed (Eq. 5), losses in upstream components, particularly from filter to diffuser where the throughflow speeds are high, are dominant. Generally, a major fraction of losses is associated with a filter or screens installed upstream.

Table 2 gives the calculated equivalent loss coefficients for the FMRL tunnel, using Eq. (8) and the loss coefficient of wire-gauze screens. The loss coefficient of a wire-gauze screen can be found from (Collar, 1939)

$$K' = \frac{(1-\beta)}{\beta^2}, \qquad (10)$$

where β is the open-area ratio of the screen. The open-area ratio for a square-mesh screen is given by

$$\beta = (1-Md)^2 = \left(1-\frac{d}{l}\right)^2, \qquad (11)$$

where d is the wire diameter; M is the mesh, defined as the number of openings per unit length – traditionally given in inch; and l is the width of the mesh. For further details on the loss through screen, see Part II. The results of the calculation are compared with those of the measurement in terms of static pressures at strategic upstream locations in Table 3.

At this point, it is worthwhile to discuss losses associated with various components of the tunnel, in general context as well as in the context of the present tunnel. Loss through a filter, parameterized as K_F, depends on the effective air speed through the filter which is, in turn, directly related to the effective flow area of the filter. In the case of the present tunnel, screens were used at the inlet of the blower as a safety guard. From Tables 2 and 3 it is obvious that the loss through the safety-guard screens accounts for most of the loss in the tunnel. This is due to the fact that the nominal inlet area of the blower, which is 15.75 inches in diameter and 1.12 times of the test section area, is relatively small, resulting in high flow speed and, thus, high loss. This loss can be reduced by using commercially available filters with larger effective area. The improvement we shall make in the future.

Two interesting points regarding the loss through the safety-guard screens were noted during the attempt to account for the losses as calculated from Eqs. 8 and 10 against the measurement results. Namely and firstly, it was noted that the *effective* inlet area of the blower was considerably less than the *nominal* inlet area, at least as far as the loss through the inlet screens was concerned. Here, the nominal inlet area is calculated from the nominal inlet diameter of the blower and the effective inlet area is calculated from the average velocity measured upstream of the screens and the volume flowrate through the tunnel measured at the contraction exit. This reduction in the effective inlet area results in a higher effective velocity through the screens. As a result, the actual pressure drop through the screens is higher than the calculated result based on the nominal inlet area. (The values given in Tables 2 and 3 are based on the effective inlet area.) Specifically, the effective inlet area was found to be only 10 inches in diameter, approximately 40% of the nominal inlet area. If the leakage through the tunnel is estimated to be 10% of the volume flowrate at the contraction exit, the effective inlet area still accounts for only 44% of the nominal inlet area. This would translate into an underestimate of the loss through inlet screens by a factor of 5 if the nominal inlet area was used in the calculation. This point further emphasizes the need for a filter with large effective area if the loss is to be reduced.

Secondly, it was noted that, if two screens of considerably different mesh sizes are overlaid, e.g., like the present case for which the meshes are 2.5 and 16, the effective loss coefficient can be estimated, using Eq. 10, from the effective open-area ratio which is the product of the open-area ratios of the two screens. This is probably due to the fact that the actual open-area ratio of the overlaid screens is approximately equal to the product. The scenario is expected to be more complicated, however, for the screens of comparable and small mesh sizes owing to the dependence of the size of the actual open area on the pattern of the overlaid.

Similarly, loss in a settling duct, parameterized as K_{SD}, is mainly caused by the screens installed. Since the area of the duct is approximately equal to the exit area of the blower (a diffuser is used to increase the flow area), the flow speed is quite high and considerable loss occurs. On the other hand, one may choose a longer duct with less number of screens to allow the flow to settle less violently, but this requires a longer space for the tunnel.

Similar, but more crucial, consideration applies to loss in a screened diffuser, parameterized as K_{DS}, owing to the possibility of large-scale separation in the diffuser and, consequently, unsteadiness of the mean flow in the test section. That is, to prevent a large-scale separation with less number of screens and less loss, the diffuser must have small divergence angle. This, again, requires a longer space for the tunnel. Further discussion of screened diffusers shall be postponed to Part II.

On the contrary, loss in a settling chamber, parameterized as K_{SC} and caused by honeycomb and screens, is rather low due to lower throughflow speed. This is also true for loss through a contraction, parameterized as K_C. And, depending upon the flow configuration being investigated, loss in the test section, parameterized as K_T, may be large or small. For example, for a boundary layer study the loss is quite small when compared with that of a model study. Finally, since all of the kinetic energy of the exit jet is dissipated in the room, $K_J = 1$.

For further details of the estimation of loss coefficients, the reader is referred to Part II, Rae and Pope (1984), and Mehta (1977).

Considerations for test-section velocity and fan power

Because the required static-pressure rise across a fan is proportional to the square of the test-section velocity, Eq. (8), the fan power is proportional to the third of the test section velocity. Figure 3 shows the normalized fan power and the unit Reynolds number, defined as V_T / ν, as a function of the test section velocity.

As discussed in Sec. 3, for a given test section size the choice of the test section velocity depends primarily upon the flow to be investigated. And, as illustrated in Fig. 3, the unit Reynolds number is linearly proportional to the test section velocity, while the power required is to the third. Therefore, a trade-off between an increase in unit Reynolds number and the power, hence the cost, required to drive the tunnel should be considered.

7. Conclusions

Because scientific researches are vital to long-term development of the country, it is important that the conducting of researches be encouraged and promoted. On the other hand, it is equally and fundamentally important for the researcher to be able to design and develop some of his basic research facilities. One of the basic research facilities in the field of fluid mechanics is a wind tunnel. This series of three papers reports the design and development of the FMRL 60x18 cm^2 wind tunnel. It is hoped that the design and development reported herein will be of value for fluid dynamics research community in Thailand.

This first part of the series discussed the generals, the specifics, and the practical aspects of wind tunnel design. Performance indices and design considerations regarding the configuration parameters such as test section shape and size, test section velocity, type of wind tunnels, contraction ratio, settling chamber shape and size, and losses were discussed. Particularly, the dependency of the test section shape and size on the flow configuration to be investigated was emphasized, and the comparisons in some important aspects between wind tunnel of various types were made. Examples from various studies of various flows were given.

From these considerations, taking into account the practical aspects especially those concerning cost and space available, it was then concluded that a wide-angle screened-diffuser blower tunnel was suitable for the local laboratory. The reasons were the flexibility of this type of tunnel in accommodating various flow configurations for various researches as well as the minimal space required. General description of the resulting tunnel was then given.

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Table 1. See next page.

Table 2. Estimated equivalent loss coefficient for each component.

Component	**Estimated *K***	**% Loss**
Filter (screens)	4.1	70
Flexible duct	0.26	5
Settling duct	0.3	5
Screened diffuser	0.14	2
Settling chamber	0.06	1
Contraction	0.01	~ 0
Test section (not installed)	-	-
Free jet	1	17
Total	5.9	100

Table 3. Estimated and measured static pressure at strategic upstream locations.

Component	Estimated static pressure, $P\text{-}P_{atm}$ (mm WG), Eq. (8)	Measured static pressure $P\text{-}P_{atm}$ (mm WG)
Filter (screens)	-100 (at exit)	-97 (at exit)
Flexible duct	14 (at exit)	9 (at mid duct)
Settling duct	11 (at mid duct)	12 (at mid duct)

Table 1. Examples of low-speed closed test-section wind tunnel from various studies.

References	Return	Blower/ Suction	Test Section Size ($WxHxL$)	Non-dimensionalized Test-Section Size*			Test Velocity	Contraction Ratio	Investigated Flows
				$\tilde{W}$	$\tilde{H}$	$\tilde{L}$			
Aronson et al. (1997)	Closed	N/Ap	1.25 x 1.80 x 2.90 m^3	15.6	22.5	36.3	5 m/s	6.2	Shear-free turbulence. (Grid-generated turbulence over moving wall.) Length scale = Mesh size, 80 mm.
Champagne (1978)	Closed	N/Ap	2 x 3 x 20 ft^3	16	24	160	~ 5 - 30 m/s	10	Fine scale structure of cylinder wakes. Length scale = Cylinder diameter, 0.375-1.5 in.
Chandrsuda and Bradshaw (1981)	Open	Blower	762 x 127 (178) x >760 mm^3	15	2.5 (3.5)	> 15	31.5 m/s	N/A	Reattaching mixing layer. Length scale = Step height, 51 mm.
Clauser (1954)	Open	Blower	3 x 4 x 37 ft^3	3.3	4.4	40	6 - 40 ft/s	15	Turbulent boundary layers in adverse pressure gradients. Length scale = Boundary layer thickness, 2-20 in.
Mcmahon et al. (1971)	N/A	N/A	108 (dia.) x 96 x 48 in^3	54	48	24	50 ft/s	N/A	Turbulent jet in crossflow. The circular test section is installed with a flat plate of 66 in. wide at the bottom. Length scale = Jet diameter, 2 in.
Moussa et al. (1977)	N/A	N/A	0.61 x 1.22 x 6 m^3	26	52	254	8.5 m/s	N/A	Turbulent jet in crossflow. Length scale = Jet diameter, 2.36 cm.
Muck et al. (1985); See also Hoffman et al. (1985)	Open	Blower	762 x 127 x > 2500 mm^3	35	5.7	>114	33 m/s	N/A	The effect of convex and concave curvatures, respectively, on turbulent boundary layers. Length scale = Boundary layer thickness, 22-33 mm.
Schwarz and Bradshaw (1993)	Open	Blower	762 x 762 x 3748 mm^3	25.4	25.4	125	26.5 m/s	7	Three-dimensional turbulent boundary layers. Length scale = Boundary layer thickness, 30 mm.
Simpson et al. (1981)	Open	Blower	36 x - x 300 in^3	2.9	-	24	60 ft/s	4	Separating turbulent boundary layer. Adjustable wall height. Length scale = Boundary layer thickness, 0.492-12.518 in.
Smith and Mungal (1998)	Open	Suction	54 x 54 x 94 cm^3	54	54	94	5 m/s	N/Ap	Turbulent jet in crossflow. Length scale = Jet diameter, 2-10 mm.
Westphal et al. (1987)	Open	Blower	80 x 20 x 300 cm^3	20	5	75	27 m/s	7.5	Vortex/Boundary-layer interaction. Length scale = Boundary layer thickness, 4, 6.2 cm.
Wygnanski et al. (1986)	Closed	N/Ap	2 x 3 x 20 ft^3	96	144	960	2 - 35 m/s	10	Small-deficit turbulent plane wakes. Length scale = Cylinder diameter, 6.35 mm.
FMRL Tunnel	**Open**	**Blower**	**60 x 18 x 240 cm^3**	**20**	**6**	**80**	**13 m/s**	**9.3**	**Effects of vortex-generator configurations on different flow regimes of diffusers Length scale = Boundary layer thickness, 3 cm**

* Non-dimensionalized test-section size is defined as the ratio between the test-section dimension and the relevant length scale of the flow. (See the relevant length scale in the rightmost column.) Since the appropriate test section dimensions may depend on other parameters of the flow, the reader is referred to the cited references for further details. N/Ap = Not Applicable, N/A = Not Available.

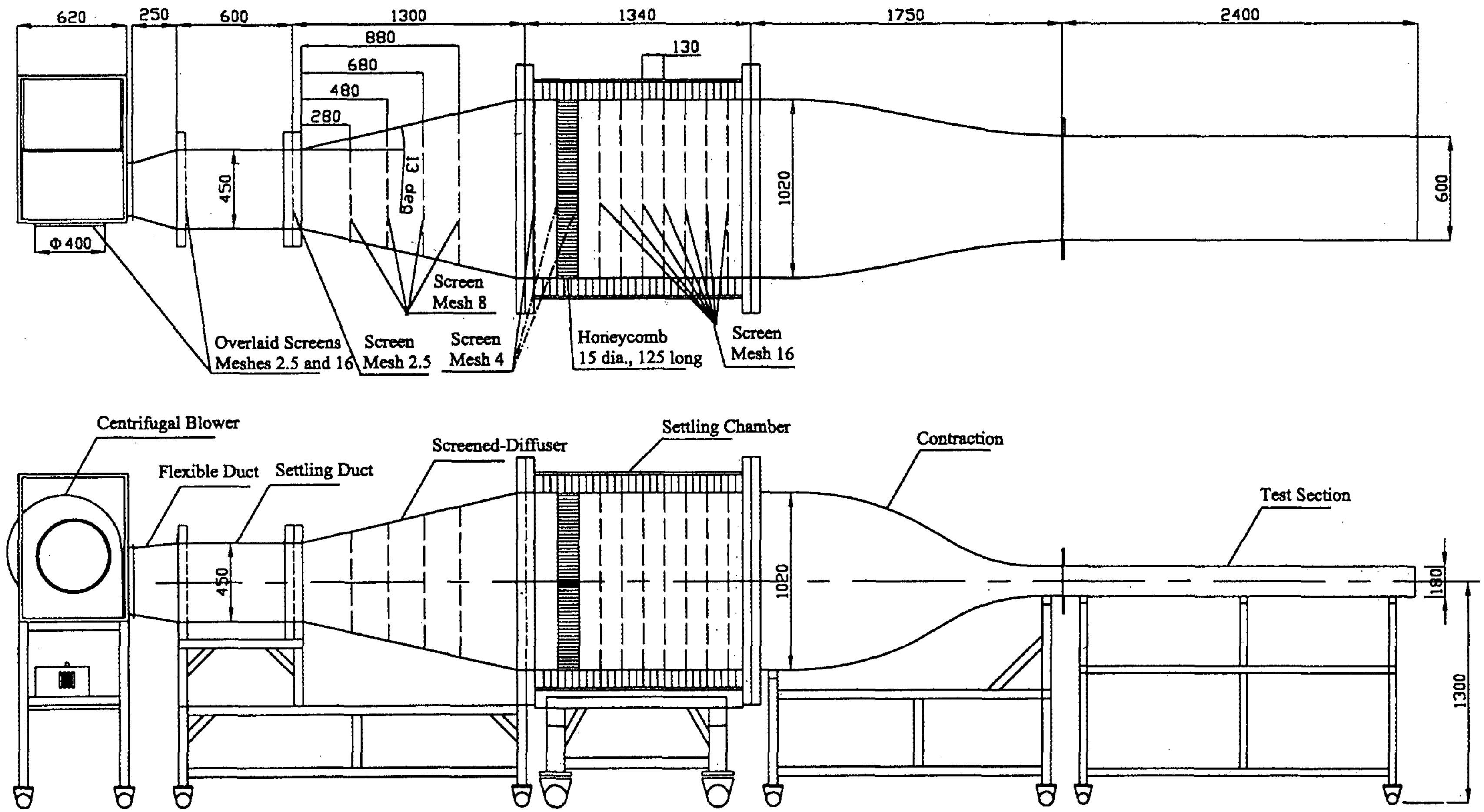

Fig. 1. Schematic diagram of the FMRL 60x18 cm^2 wind tunnel. All dimensions are in mm.

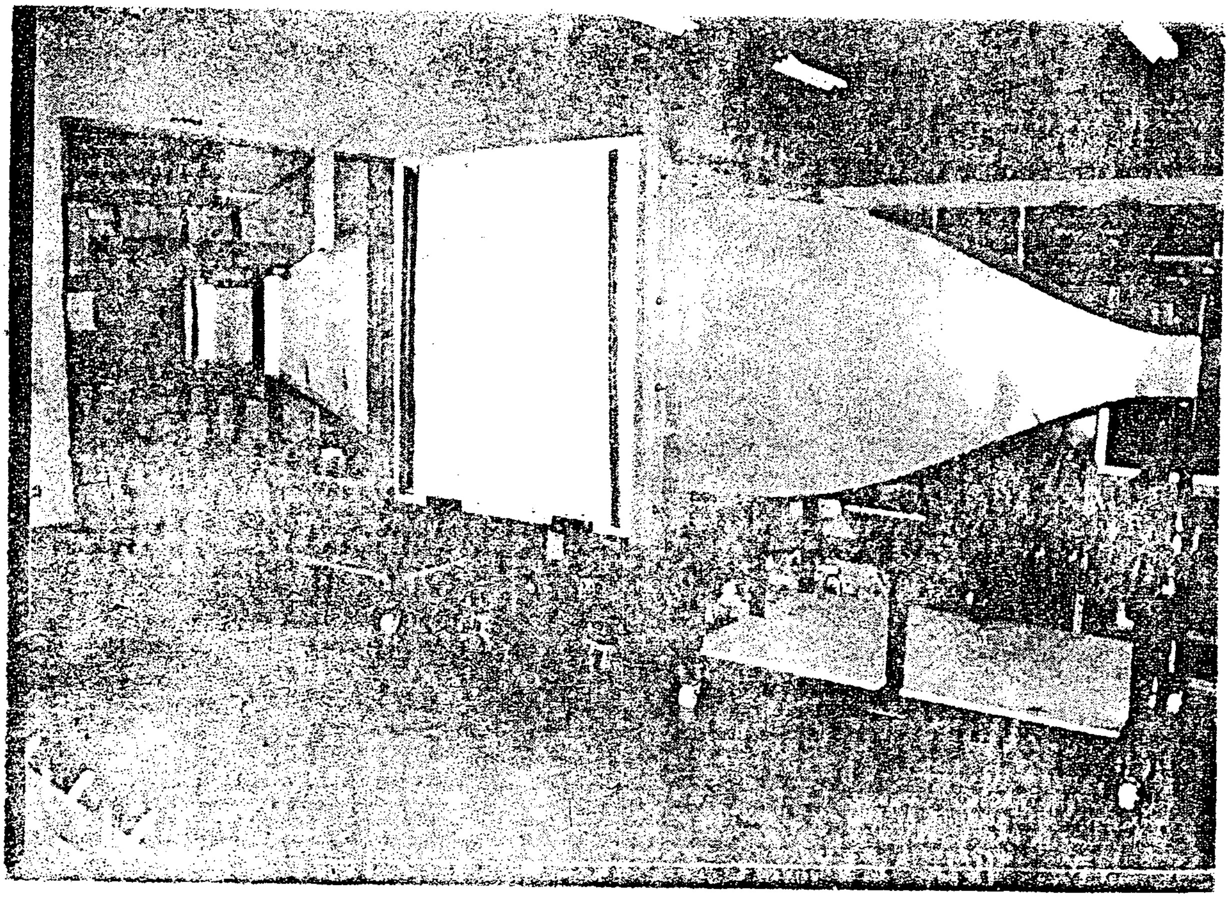

Fig. 2. Photograph of the FMRL 60x18 cm^2 wind tunnel.

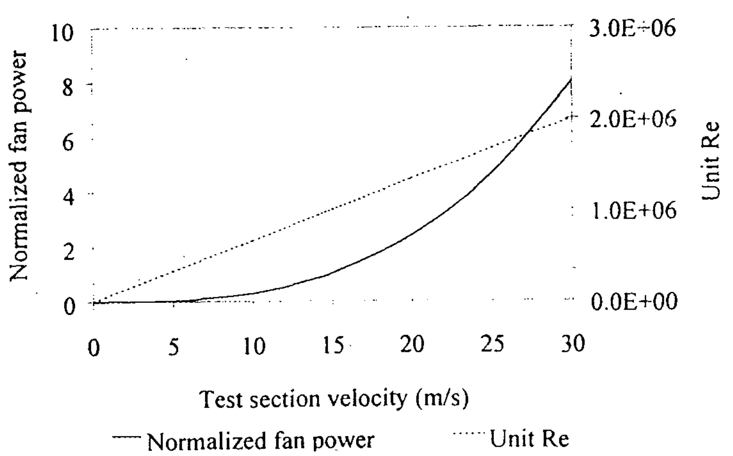

Fig. 3. Normalized fan power and unit Reynolds number as a function of test section velocity. The fan power is normalized by the power required at the test section velocity of 15 m/s.