FLOW MEASUREMENT BY LASER DOPPLER VELOCIMETER IN A CROSS-FLOW FAN FOR AIR-CONDITIONING USE

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ABSTRACT

The cross-flow fan discussed here is incorporated into an air conditioner that has the inlet on top and does not have apertures in front; that is, it has a flat front panel. In order to get fundamental characteristics of the cross-flow fan, a flow measurement system by laser doppler velocimeter (LDV), which can obtain both velocity data and turbulence data, was adopted. The LDV used in this study is a two-color, four-beam system, which is suitable for measuring unsteady flow such as the flow in a cross-flow fan. This paper describes the variation of the internal flow in the cross-flow fan and the vortex movement that occurs when the position of the flat front panel, or the distance between the tongue and the impeller, or the shape of the suction region is changed.

INTRODUCTION

The room air conditioner has come into widespread use in recent years. Its fundamental performance (i.e., heating and cooling efficiencies) has been regarded as its most important aspect, but users have also shown interest recently in a design that harmonizes with room decor. A thinner indoor unit with a flat front panel, whose cross section is shown in Figure 1, is expected to be developed soon.

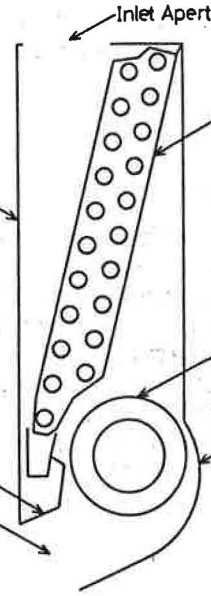

Figure 1 *Indoor unit of room air conditioner*

Most research on cross-flow fans has been concerned with the relationship between the flow rate and the pressure. Measurement of the internal flow has rarely been done because of the difficulty in moving a measuring point. Only a few papers report measurement with a simple model (Murata et al. 1975) and flow visualization with water. In a previous paper (Matsuki et al. 1988), we reported a method of measuring the internal flow by pitot tube and showed that the performance of a cross-flow fan with a heat exchanger could be comprehended by investigating the total pressure at the vortex center.

Figure 2 shows the internal flow of a conventional indoor unit measured by pitot tube (Matsuki et al. 1988). The vortex in the cross-flow fan stays near the tongue in this figure. The flow, which is sucked above the impeller, passes inside the impeller, centering around the vortex, and blows from the impeller. Thus, the approximate position of the vortex is predicted by the direction of the flow inside the impeller or the flow blown from the impeller. The vortex of a cross-flow fan always moves; therefore, a measurement system for turbulent flow is necessary in order to measure the flow change, which follows with the vortex movement and cannot be obtained by the pitot tube method. We adopted a system that measures the internal flow of a cross-flow fan by laser doppler velocimeter (LDV) and collected the data necessary to develop a numerical model of a cross-flow fan. We attempted to obtain the per-

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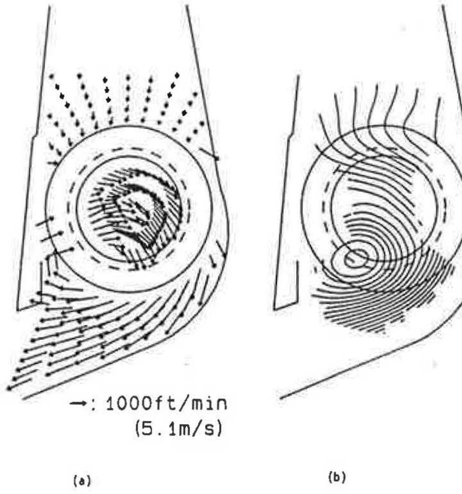

***Figure 2** Flow in the conventional indoor unit*
(a) flow vectors
(b) streamline

formance characteristics of a cross-flow fan by mean flow patterns and to express the flow state by turbulence energy contours.

EXPERIMENTS

Experimental Unit

The test unit described here is the indoor unit of a split-type room air conditioner of 9000 Btu/h (2.6 kW) cooling capacity. It consists of an impeller, a rear guider, a flat front panel, and a tongue. The cross section of this unit is shown in Figure 3a, and the structure of the impeller is shown in Figure 3b. The test unit is approximately half the length of the indoor unit, and both sides are sealed by clear acrylic boards. The blades of the impeller are held by hollow plates. The impeller is attached to the driving motor shaft, and the other side of the impeller is supported with a bearing whose inner diameter is the same as the diameter of the inner edges of the blades. It rotates at a fixed speed of 1400 rpm by supplying a controlled voltage to the driving motor. The flat front panel can be moved and, consequently, the depth of the test unit and the width of the outlet aperture can be changed. The tongue, which is parallel to the rear guider, is fixed at the bottom edge of the front panel and can easily be exchanged.

Measurement System Hardware

LDV is often utilized for investigation of turbulent flow because it has a high resolving power for both time and space and makes non-contact measurement possible. The velocity is calculated from the doppler signals that occur when the seed particles traverse the intersection of the two laser beams, and the velocity data are expected to have a higher accuracy. However, the data need to be treated very carefully because of various mingled noises.

The back-scatter-type LDV system (Figure 4) discussed here has two colors and four beams. Its laser source is an argonion that has 514.5 nm (green) and 488.0 nm (blue) lines and a maximum power of 2 W. The blue and green beams are utilized for horizontal and vertical velocities, respectively. It is generally thought that the internal flow of a cross-flow fan is two-dimensional along the planes crossing the impeller axis at right angles. Therefore, laser beams are irradiated from the bearing side of the impeller to the plane nearly at the middle of the test unit, where the flow is not influenced by both sides of the test unit and the plates of the impeller.

The light intensity at the measuring spot in the system becomes weaker because the laser beams are irradiated through the acrylic board. Therefore, a beam expander, beam collimator, and beam steering modules are used to minimize the intersection size of the laser beams and to increase the signal-to-noise ratio to the scattered light signal.

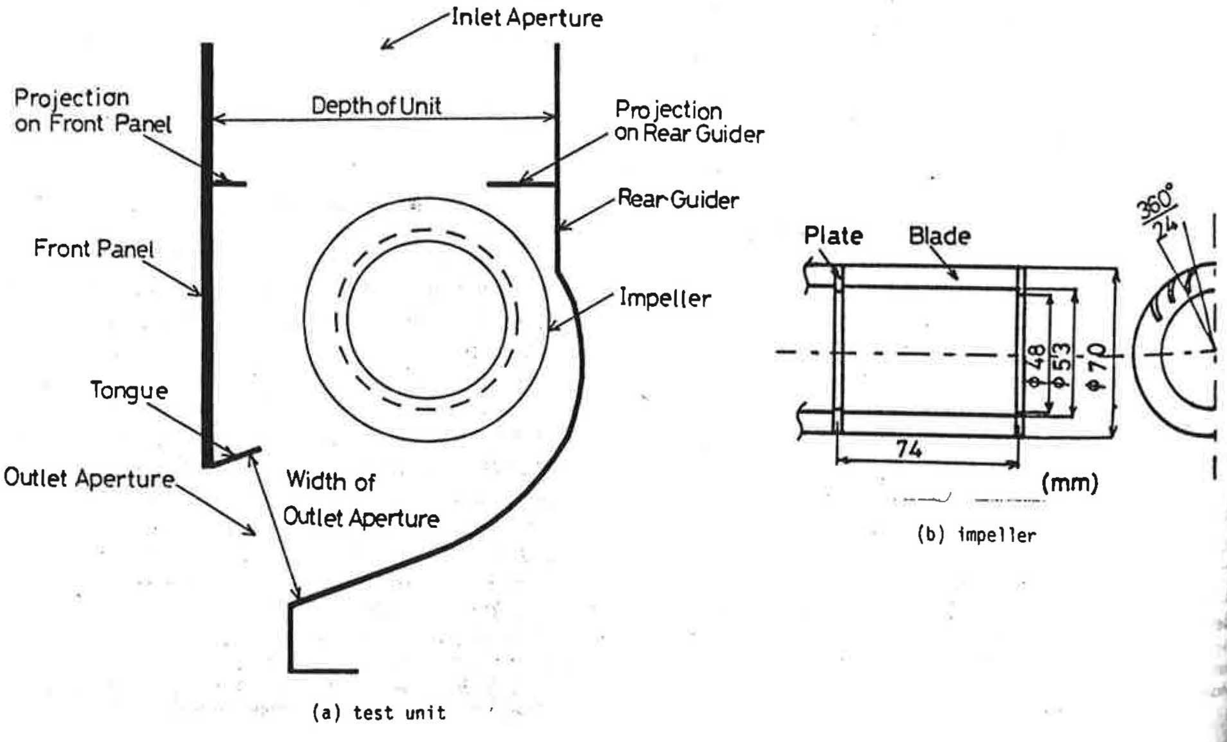

***Figure 3** Test unit and impeller*

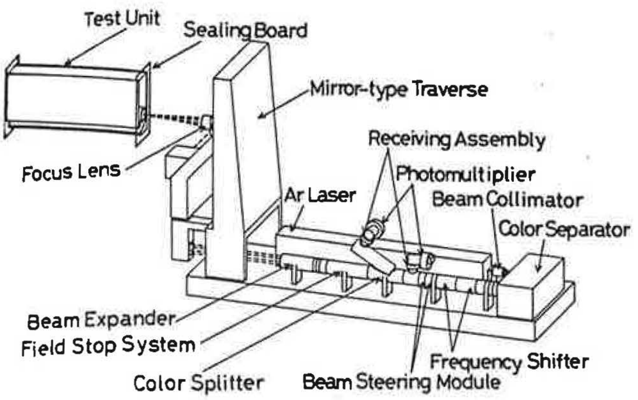

Figure 4 *Outline of apparatus*

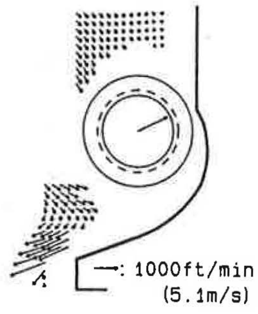

Figure 6 *Flow pattern with no flat front panel*

A field stop system is used to reduce the effects of background flare or laser light reflection through the acrylic board. Low-velocity flows and flow reversals by the vortex movement exist in a cross-flow fan. Consequently, frequency shifters are installed in the LDV system. The measuring spot, which is automatically indicated by the computer, is altered, with the result that the mirror-type traverse equipment moves the focus lens at the tip of the system.

The doppler signal from the photomultiplier is converted by the counter-type signal processor to the frequency signal, which is proportional to the velocity, and then converted to voltage data as velocity data. The 16-bit personal computer receives the data through the AD converter from the signal processor, calculates the velocity data, and records them on magnetic disk or magnetic tape.

In addition to the noise made in the optical alignment, electric noises may mingle through the photomultiplier, the signal processor, or the AD converter. Efforts need to be made to distribute seed particles uniformly so the cause of the error may not be the disparity of the data density in measuring spots.

Measurement

The horizontal velocity, u, and the vertical velocity, v, at one measuring spot are measured at an interval of 0.5 ms for 10.24 s. LDV data are not continuous because data occur when seed particles traverse the intersection of the laser beams. Data are held while seed particles do not traverse the intersection. Examples of measured data at the center of the impeller are shown in Figure 5. The velocities were measured for 61.44 s in this case. The mean velocities, $\overline{u}$ and $\overline{v}$, are calculated as follows:

$$\overline{u} = \Sigma u/n_1 \quad (1)$$

$$\overline{v} = \Sigma v/n_2 \quad (2)$$

where

$\overline{u}$ = mean horizontal velocity
$\overline{v}$ = mean vertical velocity
n_1 = number of available horizontal velocity data
n_2 = number of available vertical velocity data

The relationship between the mean velocity and the velocity fluctuation around the mean velocity is expressed for horizontal and vertical velocities, respectively, as follows:

$$u = \overline{u} + \hat{u} \quad (3)$$

$$v = \overline{v} = \hat{v} \quad (4)$$

where

$\hat{u}$ = velocity fluctuation around mean horizontal velocity
$\hat{v}$ = velocity fluctuation around mean vertical velocity

The turbulence energy, E, is given as follows:

$$E = \overline{\hat{u}^2} + \overline{\hat{v}^2} = \overline{u^2} - \overline{u}^2 + \overline{v^2} - \overline{v}^2 \quad (5)$$

where

E = turbulence energy

Thus, E can be easily obtained from $\overline{u}$, $\overline{v}$, $\overline{u^2}$, and $\overline{v^2}$.

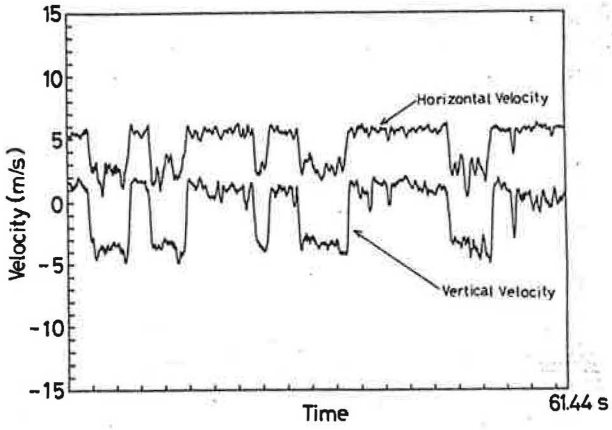

Figure 5 *Example of horizontal and vertical velocities*

RESULTS AND DISCUSSION

Because the indoor unit of a room air conditioner, as discussed here, has a flat front panel and is thinner than conventional units, it is essential that the outer diameter of the impeller be smaller and that the air inlet be located on top of the unit. First, the influence of the flat front panel will be shown. Second, the influence of the tongue length, that is, the influence of the distance between the tongue and the impeller, will be shown. Lastly, the influence of the shape of the suction region, that is, the influence of projections stuck to the flat front panel or the rear guider, will be shown.

Influence of Position of Flat Front Panel

The flat front panel can be moved so that the depth of the test unit and the width of the outlet aperture can be changed. The mean flow pattern of the test unit, which consists of the impeller and the rear guider and does not have a flat front panel, is shown in Figure 6. In the flow patterns, the vector length is directly proportional to the velocity. The impeller sucks the air from the oblique upper part and discharges it along the rear guider.

Figure 7 shows the flow vector diagrams when the depth of the unit is 3.9 in. (100 mm) and the width of the outlet aperture is 1.8 in. (45 mm), 1.4 in. (35 mm), or 1.0 in. (25 mm). Similarly, the flow vectors in the case where the depth of the unit is 3.5 in. (90 mm) are shown in Figure 8. When the test unit has a flat front panel, the flow is different than when the unit does not have a front panel. The impeller sucks the air near the rear guider, and there is upward flow along the flat front panel. The narrower the discharge aperture, the more noticeable this tendency is. It appears that the cause of this phenomenon is the upward movement of the vortex. The unit that is 3.5 in. (90 mm) deep has more of a tendency than the unit that is 3.9 in. deep (100 mm). The flow pattern when the unit is 3.9 in. (100 mm) deep and the outlet aperture is 1.0 in. (25 mm) wide is almost the same as the flow pattern when the unit is 3.5 in. (90 mm) deep and the outlet aperture is 1.4 in. (35 mm) wide. The flow in the suction region when the unit is 3.9 in. (100 mm) deep is smoother than when the unit is 3.5 in. (90 mm) deep. In short, the greater the depth, the smoother the inlet flow.

Influence of Tongue Length

The tongue is fixed at the bottom edge of the front panel and can easily be exchanged. It is generally assumed that the tongue affects control of the vortex position and division into the suction and discharge regions. The flow patterns when the unit is 3.9 in. (100 mm) deep and the outlet aperture is 1.8 in. (45 mm) wide are shown in Figure 9 for the three cases where the tongue length is 0.6 in. (15 mm), 1.0 in. (25 mm), and 1.4 in. (35 mm). The suction flow occurs near the front panel in Figure 9a, where the front panel has a tongue, while such flow cannot be seen in Figure 8a, where the front panel does not have a tongue. When the tongue is 0.6 in. (15 mm) long, it appears that the vortex position is controlled and that the vortex stays below the tongue, that is, near the rear guider. However, the flow, which once was sucked by the impeller near the flat front panel, is discharged near the rear guider and is sucked again. The longer the tongue, the more noticeable this tendency is.

In Figure 10, where the outlet aperture is 1.0 in. (25 mm) wide, the air is sucked near the rear guider by the impeller. The vortex stays below the tongue in Figure 9, where the outlet aperture is 1.8 in. (45 mm) wide, while the vortex has moved above the tongue in Figure 10.

Figure 11 shows the velocity change at the center of the impeller in the case where the unit is 3.9 in. (100 mm) deep, the outlet aperture is 1.8 in. (45 mm) wide, and the tongue is 0.6 in. (15 mm) long. In this figure, the horizontal and vertical velocities change suddenly because the vortex of the cross-flow fan alters the positions suddenly.

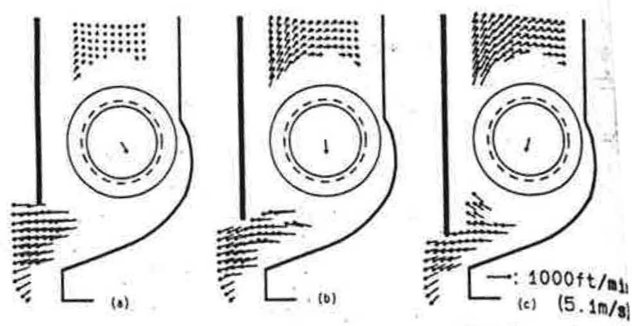

Figure 8 *Flow patterns*
Depth of unit: 3.5 in. (90 mm)
(a) outlet width: 1.8 in. (45 mm)
(b) outlet width: 1.4 in. (35 mm)
(c) outlet width: 1.0 in. (25 mm)

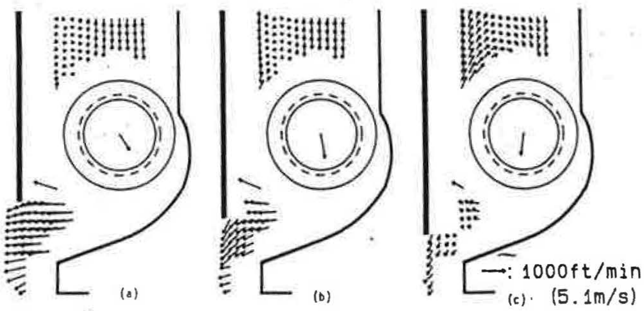

Figure 7 *Flow patterns*
Depth of unit: 3.9 in. (100 mm)
(a) outlet width: 1.8 in. (45 mm)
(b) outlet width: 1.4 in. (35 mm)
(c) outlet width: 1.0 in (25 mm)

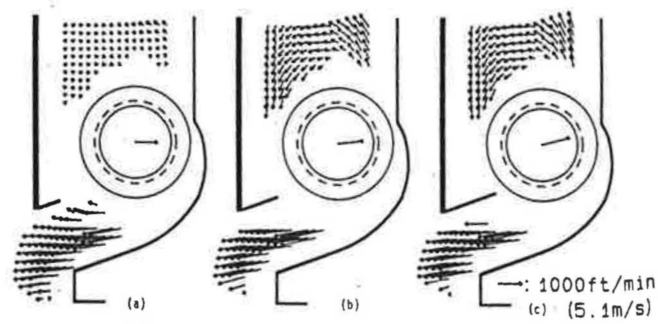

Figure 9 *Flow patterns*
Depth of unit: 3.9 in. (100 mm)
Width of outlet: 1.8 in. (45 mm)
(a) tongue length: 0.6 in. (15 mm)
(b) tongue length: 1.0 in. (25 mm)
(c) tongue length: 1.4 in. (35 mm)

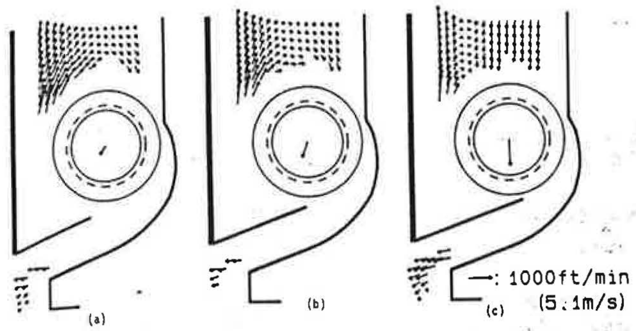

Figure 10 *Flow patterns*
Depth of unit: 3.9 in. (100 mm)
Width of outlet: 1.0 in. (25 mm)
(a) tongue length: 2.2 in. (55 mm)
(b) tongue length: 2.6 in. (65 mm)
(c) tongue length: 3.0 in. (75 mm)

Influence of Shape of Suction Region

Originally, the indoor unit of the room air conditioner (shown in Figure 1) had a heat exchanger. In a previous paper (Matsuki et al. 1988), we showed that the heat exchanger created turbulence and obstructed the flow. Here, the projection by way of the obstruction is stuck to the flat front panel. The unit is 3.9 in. (100 mm) deep; the outlet aperture is 1.8 in. (45 mm) wide; the tongue is 0.6 in. (15 mm) long. The flow of the test unit, which projects 0.4 in. (10 mm) at a height of 1.6 in. (40 mm) from the impeller center on the front panel, is shown in Figure 11a. In this case, the suction flow into the impeller, which appears in Figure 9, is obstructed, and the flow runs from the front panel to the rear guider. Figure 11b shows where the test unit has the same projection on the front panel as the foregoing and a projection of 0.8 in. (20 mm) at a height of 1.6 in. (40 mm) from the impeller center on the rear guider. The suction flow runs smoothly from top to bottom, and it appears that the projection on the rear guider is effective when flow fluctuation caused by the projection on the front panel occurs.

Turbulence Energy

Flow fluctuation and flow change in a cross-flow fan occur because turbulence occurs or the vortex moves. Figure 11a shows that flow is obstructed and turbulence is created when the unit has a projection on the front panel.

A comparison of the turbulence energy between the case where the unit has a projection on the front panel alone and the case where the unit has projections on the front panel and on the rear guider is shown in Figure 12. The turbulence energy in the suction region of the former is larger than the energy of the latter. It is known that the disturbance is caused by the projection on the front panel. However, there is no difference in the discharge regions of both cases. Thus, the turbulence energy obtained by the LDV system effectively estimates the flow state, especially the disturbance.

CONCLUSIONS

An LDV is applied to the measurement of the internal flow of a cross-flow fan that is used in a room air conditioner. The mean flow patterns and the turbulence data, which will be utilized for the verification of the numerical model, were obtained. However, discussion of the volume flow rate and detailed vortex movement could not be made because the spots near the front panel, near the rear guider, around the impeller, and inside the impeller cannot be measured.

Characteristics that were made clear in this paper include:

1. When there is a flat front panel, the suction flow occurs near the rear guider. The flow near the front panel runs upward.
2. When the front panel has the tongue, the suction flow occurs near the front panel when the outlet aperture is wide, while the air is sucked near the rear guider by the impeller when the outlet aperture is narrow.
3. The suction flow runs from the front panel to the rear guider when the projection is installed on the front panel. On the other side, a projection on the rear guider improves the suction flow when the projection is stuck on the front panel.

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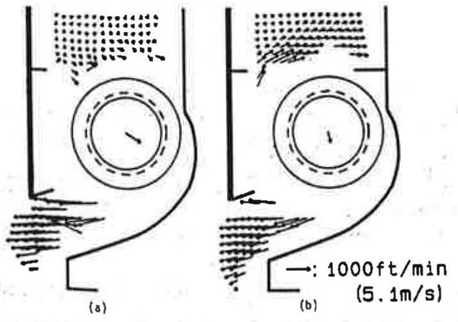

Figure 11 *Flow patterns*
Depth of unit: 3.9 in. (100 mm)
Width of outlet: 1.8 in. (45 mm)
Length of tongue: 0.6 in. (15 mm)
Length of front projection: 0.4 in. (10 mm)
Height of front projection: 1.6 in. (40 mm)
Length of rear projection: 0.8 in. (20 mm)
Height of rear projection: 1.6 in. (40 mm)
(a) front projection
(b) front and rear projections

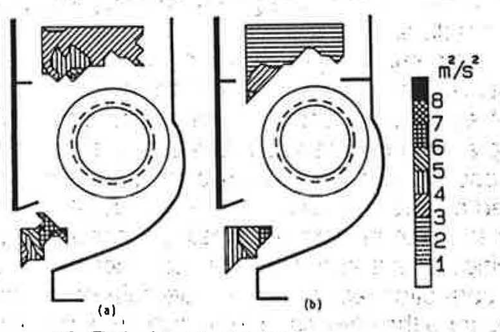

Figure 12 *Turbulence energy*
Depth of unit: 3.9 in. (100 mm)
Width of outlet: 1.8 in. (45 mm)
Length of tongue: 0.6 in. (15 mm)
Length of front projection: 0.4 in. (10 mm)
Height of front projection: 1.6 in. (40 mm)
Length of rear projection: 0.8 in. (20 mm)
Height of rear projection: 1.6 in. (40 mm)
(a) front projection
(b) front and rear projections