AIRFLOW CHARACTERISTICS OF CIRCULAR CEILING DIFFUSERS

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ABSTRACT

Circular ceiling diffusers are probably the most common types of air terminal devices used for air distribution in commercial buildings. Throw data are commonly provided in manufacturers’ product catalogues. However, detailed airflow information including airflow pattern in the outlet region, jet centerline velocity decay coefficient (K value) and jet entrainment are not usually available.

This paper presents a series of detailed measurements of airflow characteristics for a vortex diffuser and two multi-cone circular diffusers. The flow patterns and turbulence characteristics in the diffuser outlet region and in the room were measured by using a three dimensional ultrasonic anemometer. In the region adjacent to the ceiling (0.08 m from the ceiling), the air velocity was measured by using a hot-wire anemometer. The results show that the flow patterns in the vicinity of outlet region of the vortex diffuser are three dimensional and highly turbulent. Also, inappropriate design of the multi-cone circular diffuser results in “dumping” of the supply air to the occupied region of the room. The K values of the vortex diffuser investigated are in the range of 2.1 to 2.3. For the multi-cone circular diffusers, the K values cover a large range and are related to the design of the geometry of the diffuser. These detailed measurements are useful for evaluating numerical simulation models as well as for understanding the behavior of room air motion created by different diffusers.

1. INTRODUCTION

Circular ceiling diffusers are probably the most common types of air terminal devices used for air distribution in commercial buildings. Throw data are commonly provided in the manufacturers’ product catalogues. However, the detailed airflow information including airflow patterns in the outlet region, jet centerline velocity decay coefficient (K value) and jet entrainment are not usually available.

Small differences in the design of circular ceiling diffusers can greatly affect the diffuser’s air distribution performance. For example, the flow pattern is very much related to the magnitude of the angle between the jet outlet and the ceiling, φ. Little of this information is reported in literature. Hirano [1] reported on detailed isothermal measurement of flow pattern 0.1 m under the exit plane of a three-cone circular ceiling diffuser and observed notable “dumping” flow patterns. Hu et al. [2] compared cold air distribution (with a temperature of 8 °C) in the occupied zone of a room equipped with various diffusers including a nozzle type diffuser, a multi-cone circular ceiling diffuser and a vortex diffuser.

The flow pattern produced by the multi-cone circular diffuser is influenced by the angle, φ.

Becher [3] presented a correlation for jet centerline velocity along the ceiling for a single cone diffuser with angle φ < 30. By using a hot-wire anemometer, Jackman [4] conducted series of measurements for air movement in rooms with ceiling mounted diffusers, including multi-cone circular diffusers and multi-cone square diffusers. Nielsen [5] measured the three-dimensional wall jet from grilles and registers. Detailed velocity information close to the diffuser is not reported. The K values reported by Jackman and Nielsen were based on the diffuser neck velocity and diffuser neck area. The K values indicated in the ASHRAE Handbook - Fundamentals [6] are mostly based on research results published more than four decades ago [7].

In the family of circular ceiling diffusers, the vortex diffuser, as shown in Fig. 1, has a relatively high entrainment due to the swirl of the exit air, which creates a more thorough mixing of supply air and room air than with most other diffusers. The swirl effect is caused by the stationary radial guide-vanes which increase the turbulence level by imparting a spiral twist or swirl to the supply air. The control disk (Fig. 1) of the vortex diffuser can be adjusted, to the lowest level resulting in a horizontal flow, and to the highest level resulting in a downward flow. So the vortex diffuser is a
variable outlet area diffuser. Although currently on the market, the authors have been unable to obtain detailed technical performance data for it.

Because of the lack of the detailed technical information for either multi-cone circular diffusers or vortex diffusers, this paper focuses on detailed measurements of airflow characteristics specifically for these two types of diffuser. Therefore, the objectives of this study were: (1) to obtain detailed flow characteristics of the isothermal jets created in the vicinity of the outlet by a vortex diffuser and two multi-cone circular diffusers (shown in Fig. 2 and Fig. 3), (2) to study the influence of various geometry parameters on the diffusion performance for the multi-cone circular diffusers, and (3) to examine whether the induction due to twist vanes of a vortex diffuser is sufficiently high to have a significant effect on room air motion.

2. DESCRIPTION OF EXPERIMENTS

A full-scale environmental chamber (length (L) x width (W) x height (H) = 3.8 m x 3.6 m x 2.95 m) was constructed following the ANSI/ASHRAE 130-1996 [8] standard, as shown in Fig. 4. The layout and type of air diffusers could be changed according to the various experimental needs. Maximum supply air volume from the air-handling unit (AHU) of this system was 236 Ls⁻¹ [500 cfm] which was able to cover a wide range of airflow tests. Note all measurements were conducted under isothermal condition. The air volume flow rate was measured by standard nozzles which were located upstream of the diffusers. Note that the measurements were conducted under isothermal conditions.

Fig. 1: Vortex diffuser used in this study

Fig. 2: Three cone-circular ceiling diffuser

Fig. 3: Six-cone circular ceiling diffuser
The flow patterns and turbulence characteristics in the diffuser outlet region and in the room were measured by using a three-dimensional ultrasonic anemometer. The experimental setup is shown in Fig. 5. In the region adjacent to the ceiling (0.08 m from the ceiling), the velocity magnitude measurements were conducted by using a hot-wire anemometer. The three-dimensional ultrasonic anemometer and the hot-wire were mounted individually at the extension end of an XYZ mechanical traverse table which was driven by personal computer controlled step motors, and can move in orthogonal directions with 0.01 mm position precision. During the measurement, the personal computer and other instruments were placed outside the environment chamber to avoid interference with the airflow.

The output data from the anemometer were A/D converted and stored in the computer for further analyses. The sampling frequency of 20 Hz was sufficient as the frequency response of the measured velocity fluctuations distributed in a range were below 10 Hz (at about -100 dB). To obtain accurate values of the time-averaged velocities and other statistical quantities, the sampling period must be sufficiently long. A period of 30 s was used as recommended by Jin and Ogilvie [9]. The principles of three-dimensional ultrasonic anemometry lie in the change of sonic traveling time relative to the air velocity. The sensors of a three-dimensional ultrasonic anemometer consist of three pairs of transmitter and receiver probe heads spaced 5 cm apart (Fig. 5). Ultrasonic pulses are emitted from each facing pair of probe heads alternatively. Since the inverse of the travel time of an ultrasonic pulse changes in linear proportion to the air velocity, the air velocity between two probe heads can be calculated from the time lag between these two probe heads.
3. RESULTS AND DISCUSSION

The different cases of experimental investigation are shown in Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Diffuser type</th>
<th>Supply flow rate Q</th>
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<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>47.2 Ls⁻¹ (100 cfm)</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>47.2 Ls⁻¹ (100 cfm)</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>23.6 Ls⁻¹ (50 cfm)</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>47.2 Ls⁻¹ (100 cfm)</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>35.4 Ls⁻¹ (75 cfm)</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>23.6 Ls⁻¹ (50 cfm)</td>
</tr>
</tbody>
</table>

A: three-cone circular ceiling diffuser  
B: six-cone circular ceiling diffuser  
C: vortex diffuser

3.1 Cases of Three-Cone Circular Diffuser

Fig. 6a shows the flow patterns and Fig. 6b shows the turbulence intensity in the vicinity of the diffuser outlet region for case 1. An apparent recirculation zone with center located at 0.13 m under the outer cone was observed under the diffuser. This is very similar to the measured results of Hirano [1] in which a three-cone diffuser was tested. The dimensions of currently tested diffuser are close to that used by Hirano, except there was a 0.016 m diameter hole in the inner cone of the diffuser tested by Hirano. For the three-cone diffuser, as expected, there was an upward air current in the inner-cone, which may result in surface condensation if cold air is supplied to a hot/humid room where the induced room air touches the inner-cone’s surface. It is noted that the supply air is eventually “dumped” under the diffuser. In such a case, it is impossible to access the jet’s centerline velocity decay coefficient (K value). In the present study, the resultant turbulence intensity (TI) at a location is defined as \( TI = (\sigma_x^2 + \sigma_y^2 + \sigma_z^2)/3 \), where \( \sigma_x, \sigma_y, \) and \( \sigma_z \) are the standard deviation of velocity fluctuation along X, Y, and Z directions, respectively, and U is the local mean air velocity at a measured point.

3.2 Cases of Six-Cone Circular Diffuser

Flow patterns in the vicinity of diffuser outlet region and the jet expansion region for case 2 (six-cone circular ceiling diffuser with Q = 47.2 Ls⁻¹ (100 cfm)) and for case 3 (six-cone circular ceiling diffuser, with Q = 23.6 Ls⁻¹ (50 cfm)) are depicted in Figs. 7a and 7b, respectively. Unlike the “downward projection” in case 1, a horizontal jet was produced due to the horizontal velocity component and the Coanda Effect. Air entrainment induced by the horizontal jet along the jet direction is very apparent, resulting in upward flow pattern throughout the measuring domain. It may be concluded that the geometry design of the multi-cone diffuser affects the flow pattern greatly, where more cones produce a better horizontal jet.

3.3 Cases of Vortex Diffuser

The symmetric test was performed at the diffuser outlet level (the plane section 0.05 m under the diffuser). As indicated in Fig. 8, a surprising octagonal shape uneven velocity profile (\( V_{max} = 3.3 \) ms⁻¹ and \( V_{min} = 0.2 \) ms⁻¹) along the radial direction of the diffuser was observed. This means that the air distributions just outside the vortex diffuser are not even. This uneven velocity distribution is mainly due to the spin caused by the twist vanes. A vertical plane section with maximum velocity was selected for further flow distribution measurements. Figs. 9a and 9b show the flow patterns in the vicinity of diffuser outlet region and the jet expansion region for case 4 (vortex diffuser with Q = 47.2 Ls⁻¹ (100 cfm)) and for case 5 (vortex diffuser with Q = 23.6 Ls⁻¹ (50 cfm)), respectively. Note that under the diffuser outlet region, the airflows are in upward directions. It was also observed that away from the diffuser the air jet traveled horizontally, attaching to the ceiling and extending to the opposite wall for case 4. No “dumping” was observed in the occupied zone. For a terminal jet velocity of 0.25 ms⁻¹, the throw distances of case 4 and case 5 were 1.5 m and 1.1 m, respectively. The corresponding drops were 0.1 m and 0.08 m for case 4 and case 5, respectively.
Fig. 6a: Flow patterns in the vicinity of diffuser outlet region for case 1

Fig. 6b: Turbulence intensity in the vicinity of diffuser outlet region for case 1

Fig. 7a: Flow patterns in the vicinity of diffuser outlet region and the jet expansion region for case 2

Fig. 7b: Flow patterns in the vicinity of diffuser outlet region and the jet expansion region for case 3
Fig. 8: Flow patterns and turbulence intensity contours at the outlet plane for case 4 (top view)

Fig. 9a: Flow patterns in the vicinity of diffuser outlet region and the jet expansion region for case 4

Fig. 9b: Flow patterns in the vicinity of diffuser outlet region and the jet expansion region for case 5
For the same supply airflow rate (case 2 and case 4), the air velocity magnitude of case 4 was measured to be generally lower than that of case 2 at the outlet, and which indicates a larger effective outlet flow area for case 4. However, airflow turbulence intensity of case 4 was higher than that of case 2 (see Figs. 10a and 10b). These differences are attributed to the turbulence created by twist vanes of the vortex diffuser. It is noted that the turbulence intensity at the outlet area of case 4 is about double that of case 2. This high turbulence results in high induction that is sufficiently high to have a significant effect on room air motion. For case 4, a strong rotation was seen at the diffuser outlet area, this rotational motion decaying to produce a straight radial flow within about three diameters (1 m) of the center of the diffuser. The turbulence intensity level of case 3 and case 5 are comparable (see Figs. 11a and 11b), which indicates that the rotation effect is maintained even for a case with low supply airflow rate.

### 3.4 K Values

The variation of centerline velocity decay coefficient (K value), based on diffuser neck velocity and diffuser neck area for cases 2 to 5 are shown in Figs. 12a and 12b, respectively. The K values for the six-cone circular diffuser and vortex diffuser are in the range of 1.9 to 2.4. The larger K values obtained for a vortex diffuser is probably due to the rotational effect created by the twist vanes.
Fig. 11b: Turbulence intensity distribution for case 5

Fig. 12a: K values obtained from the variation of centerline velocity with relative distance for the six-cone circular ceiling diffuser. Note Un and An are the diffuser neck velocity and diffuser neck area, respectively. Ux is the centerline velocity at a distance from the diffuser x.

Fig. 12b: K values obtained from the variation of centerline velocity with relative distance for the vortex diffuser. Note Un and An are the diffuser neck velocity and diffuser neck area, respectively. Ux is the centerline velocity at a distance from the diffuser x.

4. CONCLUSIONS

- It may be concluded that the geometry of the multi-cone diffuser affects the flow pattern greatly, with more cones produce a better horizontal jet.
- The air distribution patterns in a room produced by the vortex diffuser are uneven but symmetrical. This velocity distribution is mainly due to the spin provided by the twist vanes.
- The horizontal jet and turbulence at the diffuser outlet region produced by the twist vanes is very significant. The induction due to twist vanes is sufficiently high to have a significant effect on room air motion.
- Detailed measurements in this study are useful for evaluating numerical simulation models as well as for understanding the behavior of room air motion created by different types of diffusers.

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REFERENCES


