THERMAL COMFORT IN HEATING CONDITIONS WITH A CEILING MOUNTED DIFFUSER
COMPARISON OF LOBED AND CONVENTIONAL DIFFUSERS

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Abstract
The main purpose of ventilation systems is to satisfy the need of occupants in terms of thermal comfort and air quality. In the case of mixing ventilation, which is based on the use of jets initiated from one or multiple diffusers placed in the room, the diffusers should distribute the fresh air and energy for heating or cooling, in the entire occupied zone. Hence, the design of the diffusers must aim, beyond aesthetic aspect, the ability to well mix the jet with the ambient air. Enhancement of jet mixing with the ambient air by means of lobes inserted into a diffuser, has been recently proposed as a promising and low-cost solution for improving the performance of HVAC systems. In this paper, an experimental investigation is made on jet characteristics and thermal comfort generated in a full scale model room by a conventional circular ceiling diffuser and its performance is compared with an innovative lobed diffuser having similar geometry, under identical inlet conditions. A simplified manikin simulates the presence of a human body in the test room. Airflow pattern from the diffuser and its interaction with the heated manikin were analyzed with whole-field PIV technique. Thermal comfort was explored and analyzed based on traditional point measuring probes and the standard ISO 7730. It is revealed that the thermal comfort was significantly improved using the lobed circular ceiling diffuser compared to the conventional one.

Keywords – Mixing ventilation; Circular ceiling diffuser; Thermal comfort

1. Introduction
The main purpose of ventilation systems is to satisfy the need for thermal comfort and air quality for the occupants along with reduced energy consumption. These three criteria must be considered in the design of a ventilation system as they are fundamental to the thermal environment and
energy performance. A high induction level is sought because it allows an optimal mix of the treated air with indoor air such as, all the occupants will be satisfied in terms of thermal comfort and air quality. Ceiling diffusers have gained popularity since the sixties [1], and they are especially useful in spaces where side diffusers cannot be accommodated. Koestel [2] studied jet patterns using two types of radial flow outlets, i.e. the ceiling plaques and the ceiling diffusers. Based on both experimental data and jet theory, the author gives equations which could be a basis for a designer of air distribution systems to estimate air velocities in air jets from radial flow outlets under isothermal conditions. Beyond the fact that the proposed equations are probably not applicable in cooling or heating conditions, the author warns the readers, that the proposed theory is only a crude approximation of the actual conditions, since the jet has a complex nature and its behavior depends on outlet configuration. In the case of multi-cone diffusers, the author shows the importance of the angle (Φ) between the ceiling and the axis tangent to the inner surface of the cones. When the diffuser is not flush mounted in ceiling, the jet remains radial for Φ ≤ 45°, independently of the inlet volumetric flow rate. The review paper of Becher [1] gives interesting information and practical recommendations on different types of air outlets for building ventilation systems, among them, the ceiling circular diffuser. Similar equations than those proposed by Koestel [2] are given. When the circular ceiling diffuser is flush mounted, the supplied air is sucked up to the ceiling for Φ < 30 °, attaches to it and flows radially along its surface. For Φ > 30 °, the supplied air tends to form a jet downwards. As the jet is annular at the exit, a vacuum in the void space below the central part of the diffuser appears. As a consequence, a recirculation zone form in the vacuum region. Koestel [2] also mentioned that phenomenon. According to the flow rate, the airflow pattern can reach the floor and folds back toward the ceiling. If projected air does not reach the floor, a stagnant zone appears [3]. A new generation of commercial multi-cone diffusers have been developed to switch manually or automatically from one pattern to another by mechanical adjustment of the inner cones. Anyway, the jet behavior described above in horizontal or vertical discharge remain the same. In a less ancient paper than the previous, Chuah et al. [4] conducted in isothermal conditions a comparative study of a ceiling vortex diffuser to two multi-cone ceiling diffusers. In vertical pattern distribution, a recirculation zone was observed as the one mentioned in [1, 2]. Nastase et al. [5] were the first to introduce the concept of lobed diffusers in mixing ventilation to increase jet induction relative to the conventional diffusers. The authors used PIV technique to capture in isothermal condition velocity and turbulence fields in the streamwise median plane of each jet. The results demonstrate better induction for jet issued from the lobed diffuser when compared to the reference jet issued from the conventional diffuser.

To characterize thermal comfort and draught effect in the occupied zone of indoor spaces, the standards ISO 7730 [6] and ASHRAE 55 [7] have
adopted the PMV-PPD model (Predicted Mean Vote-Predicted Percentage of Dissatisfied) and the DR index (Draught Rate or Draft Risk), proposed by Fanger [8, 9]. The PMV-PPD model is one-nodal steady-state empirical model based on the heat balance between human body and his environment supposed uniform. The DR is a local discomfort index which characterize draft effect on the neck of an occupant. According to Awbi [10], the DR index may be extended to other regions but may tend to overestimate the effect of draught on these normally clothed regions of the body. Nastase et al. [5] used the DR index to quantify the impact of the lobed diffuser on the local thermal comfort. Better DR values were achieved in the occupied zone using lobed diffuser when compared to those obtained using the conventional diffuser. The authors concluded that the higher induction of jet from the lobed diffuser is responsible of the obtained better DR values. Chow and Wong [11], and Tomasi et al. [12] have also used this index to study experimentally the thermal comfort generated by mixing ventilation diffusers in a controlled environments.

The common index used to evaluate the overall thermal comfort is the PMV-PPD model. This model was used in several studies, among them those of Wan and Chao [13] and Arghand et al. [14]. Although the PMV-PPD is a global thermal comfort model, it is used by the authors in both global and local evaluation of thermal comfort generated by different ventilation systems in cooling conditions with thermal manikins simulating human presence.

In the literature, there is a real lack of coupling information between the airflow pattern generated by circular ceiling diffuser and associated thermal comfort. This paper presents an experimental investigation of air distribution patterns and thermal comfort level, generated inside a climate chamber in heating mode and steady-state thermal conditions, by a vertical jet issued from a multi-cone circular ceiling diffuser. The impact of inserted lobes into the diffuser is evaluated. The air distribution is obtained using large-scale 2D PIV technique. As in [ 13, 14], Fanger’s PMV-model is used to evaluate the global and local thermal comfort, whereas the DR index is used to estimate the discomfort due to draught effect.

2. Materials and method

- Test chamber and jet diffusers

The experiments were carried out in a full scale model room of 3470×3470×2500 mm in size, coupled to an air diffusion circuit (Fig. 1, a). The six inside faces are thermally controlled, using a hydraulic circuit composed of capillary tubes inserted in the walls and connected to a reversible heat pump. The mean ambient temperature ($T_a$) measured at the air extraction, at the bottom of the test chamber, is controlled via the hydraulic circuit integrated in the walls. The ventilation jet flow is generated by an air handling unit equipped with a fan, a heater and a chiller, followed by a plenum box including a perforated plate, a convergent and a honeycomb. The diffuser is installed at the extremity of the plenum box. The initial flow rate ($Q_s$) and
The temperature ($T_s$) of the jet are controlled with sensors placed between the handling unit and the plenum box, and again measured at the jet inlet. A simplified seated thermal manikin [15] of 8 heated parts (total power 81 W, mean surface temperature 32 °C) located at the center of the climate chamber, was used to simulate an occupant. A three-cone circular ceiling-mount diffuser is chosen to generate the jet flow (Fig. 1, b-d). The two inner cones could be adjusted manually with a screw (Fig. 1, d) to switch from vertical jet behavior (heating mode) to radial jet behavior (cooling mode). The present study is conducted in heating conditions, hence, the diffuser is set as shown in Fig. 1, d (right) to generate a vertical jet. The diffuser described in Fig. 1, b and c, is designated by “conventional diffuser” (CD). When equipped by inserted lobes as shown in Fig. 2, the diffuser is designated by “lobed diffuser” (LD). The concept of inserted lobes [16] is its ease of implementation relative to the “built-in lobed diffuser” considered by Nastase et al. [5]. With the new concept, the process of diffuser manufacturing is not changed. The passive control of the jet is obtained by vortex promoters introduced into the conventional diffuser without intrinsic changes of its geometry. Each inserted lobe is made of resin material and built by a 3D printer.

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**Fig. 1** (a) Sketch of the model room – 1 perforated plate, 2 honeycomb, 3 diffuser, 4 dropped ceiling. (b,c) Conventional diffuser (CD) and its dimensions. (d) Control-setting of jet behavior - double-headed arrow (left) indicates the movement up/down of the inner cones, the two arrows (right) indicate the position of inner cones for vertical jet generation

**Fig. 2** Lobed diffuser (LD): (a) inserted lobes mounted in the CD, (b) cross section of the LD, (c) dimensions of the inserted lobes (in mm)

- Airflow distribution and thermal comfort measurements

The velocity field was investigated using a 2D2C Dantec Dynamics Particle Image Velocimetry (PIV) system. The PIV system is composed of a
Dantec HiSense 11M CCD camera with a sensor of 4000×2672 pixels, and a Nikkor 50 mm lens, and of a dual-cavity 200 mJ laser having a wavelength of 532 nm. The acquisition rate of this system is 2Hz. The airflow is seeded with olive oil droplets generated by a laskin nozzle generator. The PIV campaign aims a global investigation of the flow, resulting from the jet and its interaction with the thermal manikin. A total of 8 PIV windows of 1000×670 mm in size each (Fig. 3, a) were assembled to construct the whole field of 1400×2100 mm. For each window, 600 image pairs were acquired and processed through an adaptive multi-grid correlation algorithm handling the sub-pixel window displacement. The final size of the interrogation window was 64×64 pixels, with an overlap of 50%. The resulting spatial resolution is 8.4×8.4 mm. Due to the small size of seeding particles, the measurement could be affected by the peak locking effect [17]. On histograms of PIV displacement data, no peak locking effect has been detected due to the high accuracy of the sub-pixel interpolation algorithm.

For thermal comfort investigation, air temperature and air speed were measured in 64 nodes of the occupied zone using thermocouples (type K, accuracy of ±0.04 °C) and hot-sphere anemometers (TSI 8475, accuracy of ±3% of the reading). The occupied zone was meshed with 16 verticals (Fig. 3, b), each including 4 sensors located at 0.1m, 0.6m, 1.2m and 1.8m, respectively. These positions correspond to the levels of ankles, waist, head of a seated occupant and head of a standing occupant, respectively. To determine the mean radiant temperature (\(T_r\)), the method described in ISO 7730 [6] and ASHRAE Standard 55 [7] based on wall-surface temperatures of the 6 faces is applied. For wall-surface temperatures measurements, each wall including the floor and the ceiling is divided into 4 subzones of equal dimensions, each equipped with one thermocouple located at its center. The temperature of the face is the mean value of the corresponding 4 subzones temperatures. The mean wall temperature \(T_p\) is the mean value of the six wall temperatures. A black globe thermometer of 150 mm in diameter, equipped with a PT100 probe (accuracy of ±0.04 °C), is used to acquire the operative temperature \(T_o\) at the point located at 1.25 m above the ground (see Fig. 3, b), centered in X direction, and offbeat at 1000 mm from the center in Y direction due to the presence of the thermal manikin (Fig. 3, a).

- **Tested configurations**

  The selected diffuser (Fig. 1, b and c) is recommended for flow rate ranging from 200 to 400 m³/h. The experimental conditions are summarized in the Table 1 for CD and LD, respectively. The inlet Reynolds number \(Re=25000\) (34400), and the inlet Archimedes number \(Ar=0.0090\) (0.0033), based on the neck area \(A_{neck}=0.02\) m², the neck air velocity \(U_{neck}=2.78\) m/s \((3.90\) m/s) and the supplied temperature \(T_s\) (Table 1), correspond to \(Q_s=200\) m³/h \((275\) m³/h). PIV measurements were carried out for \(Q_s=200\) m³/h and thermal comfort is measured for \(Q_s=200\) m³/h and \(Q_s=275\) m³/h.
Table 1. Experimental conditions

<table>
<thead>
<tr>
<th>Cases</th>
<th>( Q_s ) [m(^3)/h]</th>
<th>( T_i ) [°C]</th>
<th>( T_n ) [°C]</th>
<th>( T_r ) [°C]</th>
<th>( T_o ) [°C]</th>
<th>( T_p ) [°C]</th>
<th>RH [%]</th>
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<tbody>
<tr>
<td>CD</td>
<td>200 ±6</td>
<td>34.9 ±0.1</td>
<td>21.6 ±0.2</td>
<td>18.3 ±0.6</td>
<td>21.6 ±0.3</td>
<td>18.1 ±0.6</td>
<td>46 ±3</td>
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<tr>
<td></td>
<td>275 ±8</td>
<td>31.0 ±0.1</td>
<td>22.2 ±0.2</td>
<td>18.0 ±0.6</td>
<td>20.8 ±0.3</td>
<td>17.6 ±0.6</td>
<td>41 ±2</td>
</tr>
<tr>
<td>LD</td>
<td>200 ±6</td>
<td>34.9 ±0.1</td>
<td>21.9 ±0.2</td>
<td>18.4 ±0.6</td>
<td>21.3 ±0.3</td>
<td>18.2 ±0.6</td>
<td>63 ±3</td>
</tr>
<tr>
<td></td>
<td>275 ±8</td>
<td>31.0 ±0.1</td>
<td>22.4 ±0.2</td>
<td>18.1 ±0.6</td>
<td>21.0 ±0.4</td>
<td>17.7 ±0.6</td>
<td>41 ±3</td>
</tr>
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According to ISO 7730 standard [6] and ASHRAE 55 standard [7] for an individual office with one occupant having a sedentary activity, the recommended value of operative temperature for optimal thermal comfort in winter conditions is 22°C. The obtained values (Table 1) are close to the recommended value.

Fig. 3 (a) PIV windows in the middle cross section of the room, (b) hot-spheres anemometer and thermocouples positions, (TM: Thermal manikin)

3. Results and discussion

- Airflow pattern

The reconstructed mean velocity distributions obtained as described before (Fig. 3a) are given in Fig. 4, a1 and b1, by their isocolors and streamlines. The PIV measurements are performed for \( Q_s = 200 \) m\(^3\)/h (Table 1). The global airflow pattern in the room for the two diffusers is almost identical. The near field behaviour of the jet (Fig. 4, a2 and b2) is similar to that of confluent jets. As the jet is annular at the exit, a vacuum in the void space below the central part of the diffuser appears. This behavior has been already described by Becher [1] and Koestel [2] and has been related to the geometry of the multi-cone diffuser. Due to the vacuum, the annular jet converges vertically towards its central axis, merge (at a distance \( Z_{MP} \)) and combine in a single jet after a certain distance \( (Z_{CP}) \) downstream of the diffuser. The merging point MP is defined as the point on the central axis \( X=0 \), where the
centerline velocity $W_C=0$ (Fig. 4, a1 and b1). Upstream MP, $W_C$ is negative (see jet profiles at $Z=50$ mm, Fig. 5, a) due to the presence of the central vacuum. Downstream MP, $W_C$ becomes positive and increases gradually. Velocity profile has an M-shape from the outlet till the combined point CP (Fig. 5, a). Beginning with this point, the jet behaves as a circular jet, with maximum velocity positioned on the central axis $X=0$. It is interesting to note that with inserted lobes, $Z_{MP}$ and $Z_{CP}$ become greater relative to the case without inserted lobes (Fig. 4 and Fig. 5). This is due to the reduction of depression effect, following the high induction generated by the lobes.

Fig. 4 (a1, b1) Velocity magnitude of the jet field for $Q_s=200$ m$^3$/h - hatching zone around the manikin corresponds to the laser scattering, the magenta line represents 0.25 m/s isocontour; (a2, b2) Zoom on the vicinity of the diffuser outlet

The positions $X_{W_{max}}$ of the maximum axial velocity $W_{max}$ and the changes of $W_{max}$ are given in Fig. 5, b and c. As can be seen on these figures, the lobes are extending the coalescence of the jet and are reducing its maximum velocity. The jet width $X_{0.5}$ (Fig. 5, d) is defined as the radial distance from the jet axis where the axial velocity $W$ in the external mixing layer equals 50% of its maximum value $W_{max}$. After the combined point $Z_{CP}$, the larger values of
$X_{0.5}$ for LD relative to CD confirm the higher ambient air entrainment in the former than in the later. The gain in jet induction occurs without additional power. In fact, measurements of pressure drops according to EN 12238 standard [18] in the CD and LD cases, do not show significant differences which were at the level of the accuracy of the pressure sensor ($\pm 2$Pa). There is an important interaction between the vertical jet and the thermal manikin (Fig. 4, a1 and b1). The “shower” effect of the jet on the manikin surface generates two stagnation points, one on the head and another on the lap. The air speed around the manikin, reaches a maximum value of 1.2 m/s for $\dot{Q}_s=200$ m$^3$/h, and sure more for $\dot{Q}_s=275$ m$^3$/h, which could be a source of discomfort. For comparison, the maximum value of 0.25 m/s is recommended for the air speed in the occupied zone [7]. Without manikin in the test room, (case not shown for brevity), the jet reaches the floor and folds back toward the ceiling.

![Diagram](image1.png)

**Thermal comfort**

Thermal comfort and draught rate are analyzed through Fanger’s PMV-PPD and DR models computed on 64 nodes of the occupied zone (see Fig. 3b). Most of parameters used to estimate the two indexes are reported in the Table 1. For DR index, the turbulence intensity is not accessible with hot-sphere anemometer. ISO 7730 [6] recommends a value of 40% in this case. According to the standards [6, 7], personal parameters for PMV-PPD model as metabolic rate, mechanical work and clothing insulation were fixed at 1.2
met, 0 met and 1 clo, respectively. Fig. 6 shows the statistic distribution of the 64 nodes in terms of PPD and DR levels (A, B, C) for the two flow rates considered (Table 1). This figure reveals clearly the advantage of inserted lobes: the higher thermal comfort according to PPD and the lower local thermal discomfort environment according to DR were achieved with the LD. For $Q_s=200$ m$^3$/h, in terms of the PPD index, 55% of the data falls in the category B and 45% in the category C for CD. For LD, 10% of data moves in the category A, 84% falls in the category B and only 6% falls in the category C. In terms of the DR index, surprisingly almost all the points fall in the category A for the two diffusers (95% for CD and 97% for LD). Note that these results give the comfort level off the jet region. In the region of interaction between the jet and the manikin, local discomforts are probably more important.

For $Q_s=275$ m$^3$/h, the indexes show a slight degradation of the thermal comfort compared to $Q_s=200$ m$^3$/h. However, the LD performance relative to the reference CD is more significant in this case. In terms of DR index, 92% of data falls in the category A for LD compared to 72% for CD. The improvement is more significant in terms of PPD index, with 81%, 19% and 0% of data falling in the category B, C, and > C for LD, compared to 28%, 69% and 3% for CD. The higher thermal comfort obtained with the LD results from its ability to generate higher mixing with ambient air as revealed previously by jet flow analysis.

\[ Q_s = 200 \text{m}^3/\text{h} \]
\[ Q_s = 275 \text{m}^3/\text{h} \]

Fig. 6 Statistic distribution of PPD and DR indexes for the two diffusers, thermal comfort level of ISO 7730 standard considered

4. Conclusion

In this study, airflow pattern, jet characteristics and thermal comfort were analyzed in mixing ventilation configuration using a three-cone ceiling mount diffuser operating in heating mode. Inserted lobes introduced into the diffuser lead to significant improvement of thermal comfort without increasing of pressure drop relative the reference conventional diffuser. The inserted lobes generate higher ambient air induction into the jet, and hence produces a faster decreasing of jet velocity. The results prove that the new concept of inserted lobes increases substantially thermal comfort in the occupied zone, without
supplementary energy consumption. Furthermore, the concept of the inserted lobes is more convenient than the built-in lobed diffuser. For all these reasons, inserted lobes is a promising low-cost solution to enhance the performance of HVAC systems.

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References


