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Experimental Study for the integration of an Innovative Air Distribution System in Operating Rooms

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Abstract

Hospital buildings in general and especially the operating rooms are a challenge for building services engineers which are struggling to ensure indoor environmental conditions satisfying all the occupants. The requirements imposed by standards often lead to the discomfort: while surgeons require low temperatures for sanitary reasons, anesthesiologists and assistants feel uncomfortable and prefer warmer conditions. In past studies the estimated entrainment in the case of the jets issued from the lobed perforated panel was found to be greater than in the case of the standard circular perforated panel. The lobed flow offers a larger induction and a longer throw, a more uniform distribution of the flow, allowing thermal comfort improvement if such perforated panels were used. We integrated this concept of perforated air diffuser in the air distribution system referred to as "laminar flow ceiling" for the operating rooms in hospital environments. We found that the lobed perforated panel is performing better than the circular perforated panel in isothermal conditions for several volumetric flow rates. The special geometry do not generate supplementary noise as the sound pressure levels were determined for both grilles for different discharge flow rates while the pressure losses are less than 30 Pa in the velocity range which corresponds to standard application of the air diffusion.

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*Keywords:*Predicted Mean Vote, Thermal Environment, Thermal Manikin, Operating Room, Confort Sense

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Nomenclature

CS	Comfort Sense
mrt	mean radiant temperature
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied
RH	relative humidity
t_{eq}	equivalent temperature
t_i	indoor air temperature
t_{OP}	operative temperature
TM	thermal manikin
TSV	thermal sensation vote

1. Introduction

Spaces from hospital buildings and especially the operating rooms are a challenge for building services engineers which are often struggling to ensure indoor environmental conditions satisfying all the occupants. The requirements imposed by the standards often lead to the discomfort of users: while surgeons require low temperatures for sanitary reasons, anesthesiologists and assistants feel uncomfortable and would like warmer conditions. The patient may also have thermoregulatory problems due to non-uniformity of thermal conditions in the operating room. In addition, it was observed from the analysis of standards across the European Union, the minimum and maximum values recommended for indoor air temperature are very different for different areas of a hospital building. Another important observation is related to the fact that different types of ventilation systems have designs, sizes and very different applicability, as well as different dynamics of the resulting air flows. The literature [1] shows that in some situations, a good choice of the ventilation system and of the air distribution pattern can contribute significantly to reducing the transmission of pathogens [2-4].

On the other hand it has been shown in various fundamental fluid mechanics studies [5-9] that a jet from a lobed orifice allows increased induction compared to a jet from a circular orifice. The optimization of the geometry of the elementary orifice and of the spacing between orifices in the case of perforated air grilles was performed numerically [10-13]. It was followed by experimental exploration of the flows coming from the innovative proposed concept, at scale 1 for application in tertiary office buildings [14]. The increase in induction observed for the elementary lobed orifice was also found to be present at the scale of an entire air diffusion grille.

In this study, we propose an analysis of a perforated lobed grille for integration into the air distribution system referred to as "laminar flow ceiling" for the operating rooms in hospital environments. We wanted to experimentally test these perforated panels in real scale conditions in a climatic chamber with the dimensions of a real operating room. One of our most important concerns was related to the thermal comfort assessment methods and we proposed several approaches. Indeed, thermal comfort is a subjective term defined by a plurality of sensations and is secured by all factors influencing the thermal condition experienced by the occupant; therefore it is difficult to give a universal definition of this concept. This way, in this paper we are presenting thermal comfort evaluation of innovative perforated panels using experimental data both from a thermal manikin prototype and a standardized measurement system.

2. Experimental set-up

The two geometries being considered in this study are circular (Figure 1, a and b) and lobed cross-shaped (Figure

1, c and d). The elementary round or cross-shaped jet represents a reference for the present study. The tested perforated panels integrating the two geometries have 120 x 244 orifices arranged in 2512 mm x 1270 mm. The plates are manufactured from aluminum sheet having 1.5mm in thickness. The equivalent diameter De of the orifices is 5mm (Figure1). The measurement campaigns were performed in a climatic test cell having the dimensions 3.6m x 3.6m x 2.5m. The test cell has active walls and an air distribution system allowing several ventilation strategies to be tested. This study was performed in isothermal conditions (see Table 1). The temperature inside the cell was measured with eight PT100 temperature sensors, connected to a data acquisition device. The probes were calibrated for a temperature interval from 0°C to 32°C, with a precision of 0.2°C. Six among the eight sensors were placed in the proximity of the walls, at the center of each one. The two other sensors were placed in the center of the cell and near the jet flow exit.

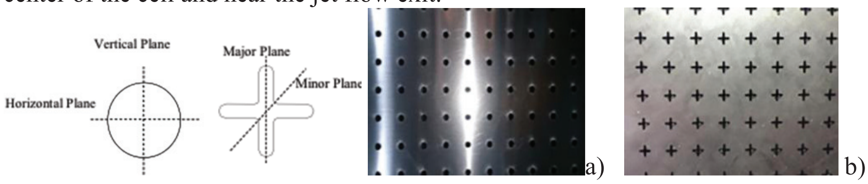

Fig. 1. Perforated panels with S=3.5De. a) Perforated panel with circular orifices, b) Perforated panel with cross orifices

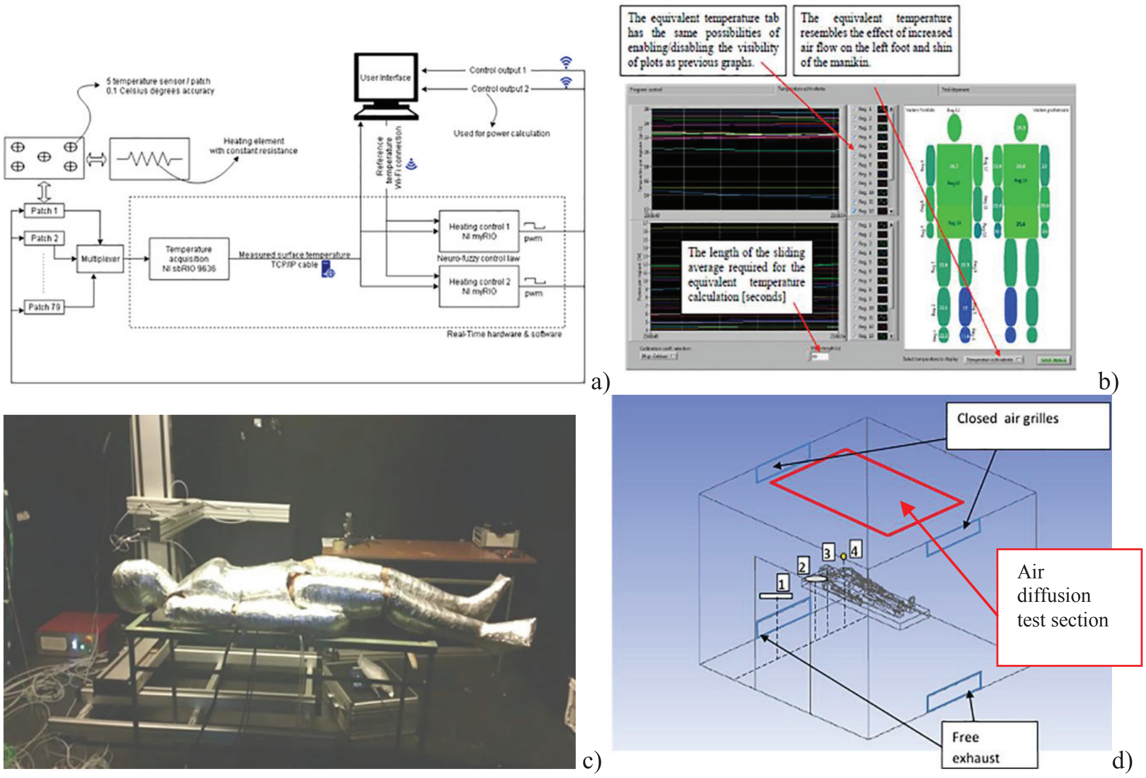

Fig. 2. a) Working principle of the thermal manikin, b) Map of the zones of the manikin, c) Photo of the thermal manikin prototype, d) Sketch of the climatic chamber with the positioning of the studied grilles and of the measurement points (1 – relative humidity, 2 – operative temperature probes, 3 – head of the thermal manikin, 4 – omnidirectional velocity probe)

The total pressure loss for each perforated panel was measured for the two studied grilles using an Energy Conservatory DG-700 micro manometer. Acoustic measurements were performed for both studied grilles using a handheld type 2250 Sound Level Meter from Bruel&Kjaer of Class 1 Precision [15-17].

The thermal comfort parameters were evaluated with the Comfort Sense system according to International Standard ISO 7730[18]. The measurements were continuous acquisitions of 10 minutes periods. Instantaneous values of the comfort parameters were sampled at each 2.5 seconds. In total there were obtained 240 instantaneous values for each mean value for all parameters: operative temperature, relative humidity, air temperature, air speed, and draught rate for each measurement. The recorded instantaneous values are reduced by the Comfort Sense software in order to obtain main index of thermal comfort, the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). The estimated values for the clothing level and for the metabolic rate were respectively 0.7 clo and 0.7 met. The positioning height of the probes on the measurement tripod of Comfort Sense was 0.95 m for the operative temperature, for the air speed probe and for the humidity probe, at the same height as the head of the manikin. The operative temperature probe was horizontal, considering the lying position of the thermal manikin in the test cell under the perforated panel.

The thermal manikin used in this study as a heating source and a measurement device is presented in Figure 2. Its working principle is to control the surface temperature of each individual zone and to record the electrical power consumption as an indication of the thermal state of each zone. Each heating circuit (i.e. zone or "segment" of the manikin) is heated as a function of the indication of a process controller which in its turn depends on the temperature recording of the sensors placed on each zone. In our case there are 79 individually controlled heating zones, each of them provided with five temperature sensors. A dedicated software interface is allowing the user to specify set-point values for each surface temperature of the zones, to monitor the evolution of each temperature of the 395 available sensors and to record the electric power consumption of the segments. The acquisition parts also processes the data to obtain reliable mean temperature of every patch using a fault detection and isolation algorithm, while de heating control devices, using the data processed by the acquisition board, generate robust and adequate signal using a neuro-fuzzy controller. The real-time hardware and software can run independently from the computer user interface, with the limitation of maintaining the last (or default) requested set point of temperature.

The computer software allows the user to load set points for several testing situations, change the set point on each patch independently and monitor the behavior of the temperature data and control system. The user can also view the average equivalent temperature displayed graphically on a simplified model of manikin and average power consumption.

In this study the 79 zones were grouped in 16 zones in order to comply to the standardized procedure of the equivalent temperature (t_{eq}) evaluation as in the standard EN ISO 14505/2 [19].

Table 1. Test conditions and aerodynamic characteristics for the two studied perforated panels

	Lobed perforation grille				Circular perforation grille			
	A_{ef}=0,1589m^2							
Q	Δp	v	N	t	Δp	v	N	t
m3/h	Pa	m/s	dB(A)	°C	Pa	m/s	dB(A)	°C
320	3.3	0.6	22.1	27.1	3.6	0.6	23.3	27.1
420	11.1	0.74	25.3	27.1	15	0.74	23.6	27
500	23.8	0.88	38.8	27.1	35	0.88	32.5	27
640	41.4	1.11	47.5	27.1	63.2	1.11	41.3	27.1
800	63.5	1.4	55.3	27	100	1.4	49.0	27.1
1000	87.8	1.74	64.5	27	-	1.74	53.9	-

3. Results

Given the special geometry of the innovative perforated panel with lobed orifices, and vortical dynamics highlighted in our previous studies [5, 20], we questioned ourselves about the pressure loss and the possible noise generation of the new air diffuser. In Figure 3 are presented the total pressure losses for the two grilles as a function of the volumetric flow rate. As it could be observed from this figure, the two grilles display similar values of the pressure losses, especially in the first part of curves up to 300 m3/h. For this range of volumetric flow rates the mean velocity at each orifice is ranging from 0.8 m/s up to 6m/s, thus corresponds to standard application of the air diffusion. One could observe that pressure losses are less than 25 Pa which is an acceptable value for an air diffuser.

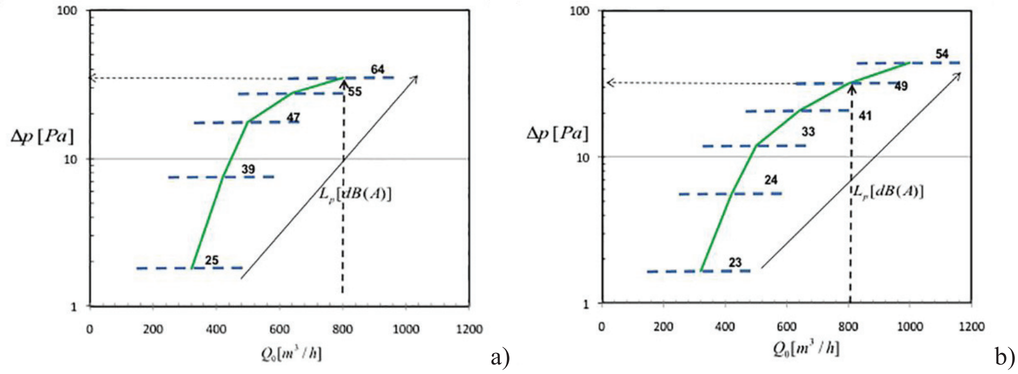

Fig. 3. Pressure losses and sound pressure levels of the perforated panels. a) circular orifices, b) lobed orifices

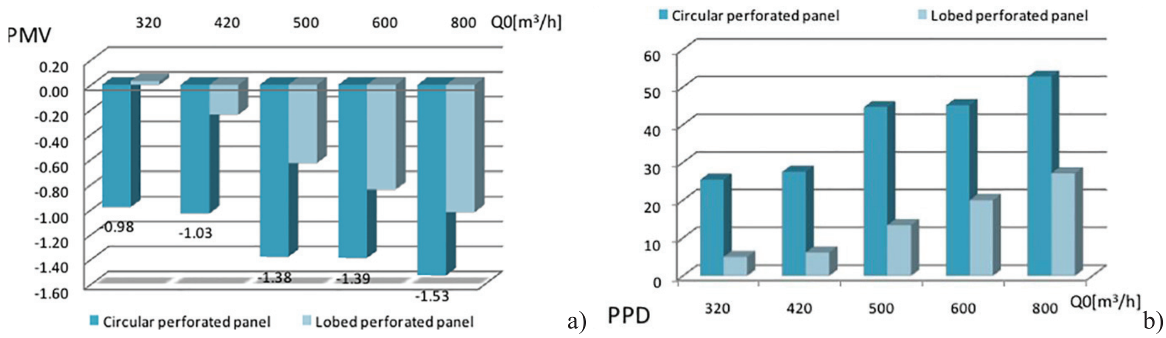

Fig. 4. Evolutions of the global thermal indexes from the ComfortSense data for several volumetric airflows. a) PMV, b) PPD

In Figure 3, we also present the global sound pressure level in the test cell as a function of the initial volumetric flow rate for two measurement positions. This global sound pressure level reflects in the same time the possible noise generation of the grilles, of the air handling unit and of air diffusion ducts. The air diffusion system is equipped with a plenum on which the perforated panels are mounted. Three cases were considered: in the first one we performed measurements without any grille mounted on the plenum, and the other two cases correspond to the functioning of the system respectively with the conventional perforated panel and the perforated panel with lobed orifices. The measurements were taken in the center of the room at 1.2 m above the floor. This height is corresponding to the limit of the occupied zone in the case when the destination of the room deals with people being seated. The condition of having at least 0.5 m between any wall and the measurements points and at least 1m from the opposite wall to the grille was respected [15-18]. The diagrams from Figure 3 show that the lobed perforated panel presents a clear an advantage against the circular perforation panels in terms of sound pressure levels.

In Figure 4, we represented the evolutions of the global thermal indexes PMV and PPD obtained from the data recorded by the Comfort Sense system for several volumetric flow rates for the two studied perforates panels. As it is displayed in this figure, it could be easily observed that in the case where the perforated panel with circular orifices was used, the Predicted Mean Vote has lower values while the Predicted Percentage of Dissatisfied has larger values. The differences between the two perforated panels are larger for smaller volumetric flow rates. They are as high as 1 point on the seven points scale of the thermal sensation for the PMV and respectively of 28% for the PPD.

Compared to classical measurement systems which give the possibility of estimating the global PMV, the thermal manikin gives the advantage of assessing locally a predicted local sensation, either through the equivalent temperature either through a derived local PMV. The thermal manikin represents a worthy tool for the thermal comfort analysis in laboratory configurations and in real field case studies being a method of investigating local discomfort trough the local distributions of the equivalent temperature of the segments of the manikin. This kind of representation allows for instance, the inspection of the uniformity of an environment. In Figure 5, we represented for each volumetric flow rate the distributions of the local teq such as defined by Nilsson [21] or in the standard EN ISO 14505/2 [19]. The same observation as for the PMV and PPD indexes could be done. Lower equivalent temperatures were found to be recorded by the different zones of our thermal manikin for the case where the circular perforated panel was employed for the lower values of the volumetric air flows while for the higher volumetric rates the lobed perforated panel shows a clear advantage. The differences between the teq for the two perforated panels were also found to be larger for smaller volumetric flow rates.

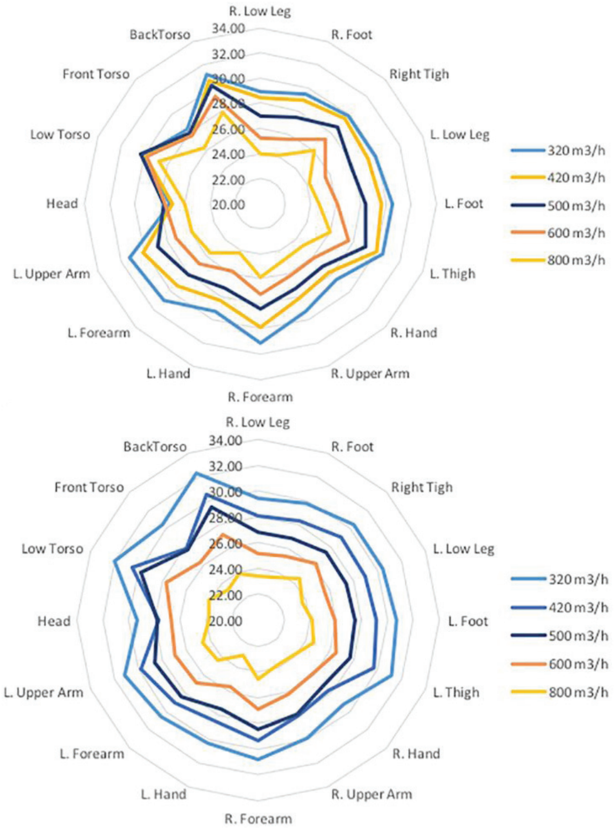

Fig. 5. Distributions of local teq obtained from the thermal manikin data for the two perforated panels

4. Discussion

In previous studies on elementary jet flows [5, 20, 22] allowed us to establish a physical link between the induction phenomenon in the near exit region of the orifice jet and the vortical dynamics that occurs in that region. It was shown that on an average the entrained flow rate in the near exit region of the cross shaped lobed jet is twice as large compared to the one of the circular reference jet. It was also displayed that the jet's throw is not altered by the gain in induction. The vortical stir, more intense in the lobed jets, leads to higher levels of the turbulent momentum flux in the region of the potential core [23]. The higher self-induction and the conservation of the jet throw in the far field is probably the result of the combination of several factors. These factors should be the conservation of the flow asymmetry, the relatively lower turbulent momentum flux levels, and the more extended boundary between the jet and its ambiance due to the strong initial entrainment [5]. In other past studies [24], the estimated entrainment in the case of the jets issued from the lobed perforated panel was found to be greater than in the case of jets from the standard circular perforated panel. The lobed flow offers a larger induction, a longer throw, a more uniform distribution of the flow, allowing thermal comfort improvement if such perforated panels were used.

As a second step of our approach, we wanted to verify these assumptions at real scale in a climatic cell, using two experimental devices for the assessment of the thermal comfort. We found that the lobed perforated panel is performing better than the circular perforated panel in isothermal conditions for several volumetric flow rates. This way, panels with lobed perforations might be a solution for the optimization of mixing ventilation in building in vertical air blowing configuration. The next logical step is to test the lobed perforated panel in cooling configuration. This investigation is under progress.

5. Conclusions

An innovative air diffuser in the form of a lobed perforated panel was experimentally tested in real scale conditions in a climatic chamber in comparison to the reference circular perforated panel. One of our most important concerns was related to the thermal comfort assessment methods and we proposed several approaches.

We found that the lobed perforated panel is performing better than the circular perforated panel in isothermal conditions for several volumetric flow rates. The special geometry of the lobed perforated panel was not found to generate supplementary noise as the sound pressure levels were determined for both grilles for different discharge flow rates. Pressure losses were also found to have similar values for both grilles and the pressure losses are less than 25 Pa in the velocity range which corresponds to standard application of the air diffusion. This way, panels with lobed perforations might be a solution for the optimization of air distribution systems for operating rooms.

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