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Field study of diffuse ceiling ventilation performance under high air change rate

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Abstract. Diffuse ceiling ventilation utilizes the entire ceiling surface to distribute airflow to rooms. The air seeps via perforations, often present in acoustic ceilings, from the pressurized plenum to the occupied zone below. In the literature, this concept has proven superior in terms of draught, even for quite high airflow rates and sub-temperatures. However, documentation of practical installations followed by measurements campaigns and in-depth analyses of the concept, are rare. Consequently, we present a study to showcase the performance of the installation under rather extreme conditions: air change rate of 20 h^{-1} and supply temperature 3-4°C below room temperature. The corresponding cooling was 56-74 W//m^2.

The investigated room was 165m^2 and 2.75m high. Numerous computers and TV screens caused significant heat loads, as well as the large windows on 3 facades of the room (West, North, East). The ventilation, equipped with a cooling coil, supplied 9200 m^3/h to maintain the temperature in the room. The airspeeds and temperatures were measured at 7 different heights (from 0.1m to 2.4m) in 26 positions.

The results showed an even distribution of the temperature in the room with measurements between 23 and 26˚C and an average temperature gradient of 0.33˚C/m (max 0.8˚C/m) while in the plenum the difference of temperature was 1.5˚C between the inlet and the opposite corner. The airspeeds were on average between 0.11 m/s and 0.17 m/s with the highest values at the ankle level. Half of the logged points had Draught Rate (DR) below 10% and all positions were below 20% except one. The airspeed exceeded 0.2m/s in less than 9% of the measurements.

For comparison, we discuss the implications of using ceiling swirl diffusers or displacement ventilation in the same context.

Keywords. Diffuse ceiling ventilation, indoor comfort, air speed, office, high air change, vertical temperature gradient, draught, Draught Rate.
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1. Introduction

The performance of diffuse ventilation was assessed multiple times under different conditions in the scientific literature. The performance was evaluated using benchmarks in standards and codes [1-3] and by comparing the solution with other ventilation solutions [4-5] in terms of draught. Often the studies are made in laboratories and limited to air change rates (ACR) and temperatures that are relevant in office or school settings. Zukowska-Tejsen [6] presented results from live ventilation operation in an office setting with ACRs in the range of 1.2, 11.5 and 17.9 h^{-1} and temperatures differences between extract and supply of 5.5 and 10.6K. The results indicated low risk of draught even at cooling load of 116 W/m^2.

This study was aimed at mapping the performance of DCV in an office setting with cooling load of 56-74 W/m^2, and ACR of 20 h^{-1} (0.015 m3/s per m^2). In this setting, high-impulse mixing would most probably cause elevated risk of draught [5, 7]. In this study, the temperatures and airspeeds were rigorously mapped and compared to standards to verify the refurbished indoor climate.

2. Methods

2.1 Facility

The room is used for the control of the metro traffic and the safety in the stations. There are always a least 5 employees in the room at the same time and the room is used 24 hours a day as the metro traffic never stops. Each employee has many computer towers and screens on his desk causing significant heat loads. There is also a wall of screens displaying the security cameras in the stations. The façade is entirely made of windows except for the wall facing South-West. The overall heat loads in the room are important. The total volume of the room is 453 m^3 (11 m x 15 m x 2.75 m).

In order to improve the indoor conditions, the room was refurbished with a new high-capacity air-handling unit and acoustic ceiling tiles from Ecophon. The new ventilation system consists of the existing air-handling unit that provides 1200 m^3/h of fresh air at any time and a new air-handling unit, equipped with a cooling coil, that provides 8000 m^3/h of recirculated air to maintain an indoor temperature (actually extract) of 23°C. The cold air is supplied in the plenum above the acoustic ceiling tiles in different places for diffuse ceiling ventilation. There are 10 extraction outlets in the room to remove the polluted air and the heat. The new ventilation unit is placed on the roof top and reaches the supply and extraction ducts through 10 holes in the slab represented in Fig. 1 with red and blue circles. The extraction ducts act as obstructions in the plenum, and as a consequence, in the perimeter area between the duct and the wall, the supplied air might not mix as easily as in the rest of the plenum. The cooling system is capable of 21 kW in normal conditions and up to 26 kW for short periods of time. It is therefore capable of handling 130 W/m^2 and maintain the indoor temperature at 23°C.

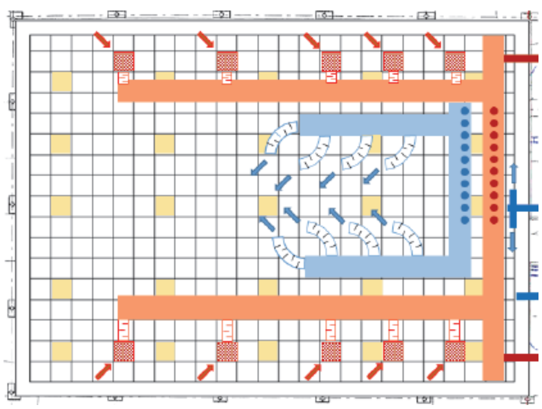

Fig. 1 - Ventilation system in the plenum. Air was distributed using pieces of flexible duct in the plenum. Extract trough ducted grilles in ceiling. Room dimensions: 11 x 15 x 2.75 m

The two air-handling units were programmed to maintain a total constant airflow of 9200 m^3/h in the room. The conditions of the test were very steady. The measurements were conducted on Friday the 2nd of July 2021 from 12:30 until 2:30 pm. There were between 6 and 8 users at the same time in the room during the measurements. As seen in Fig. 4, the temperature outside was warm and stayed between 21-24.2°C.

2.2 Measurements

The indoor comfort in the room was investigated in terms of temperature distribution and draught risks. Anemometers AirDistSys5000 from Sensor-Electronic were used to measure simultaneously the air temperature and air speeds. These devices have a high measurement accuracy and sensitivity of 0.05 m/s. Measurements were performed in 26 different positions in the room, distributed evenly except around the occupants where additional measurements were performed. For each position, 7 anemometers were mounted vertically at the heights 0.1 m, 0.3 m, 0.6 m, 1.1 m, 1.7 m, 2.0 m and 2.4 m. The data was recorded for 5 minutes with a logging interval of 2 seconds. The first and second minute were used to achieve a steady state and the reported results represent average values of the last three minutes.

The plenum temperature and relative humidity were measured in 2 different places (S1 and S2 in Fig. 2), next to the inlet and in the opposite corner where the temperature difference is believed to be the warmest in the plenum. Also two room sensors (S3 and S4) measured room air temperature and relative humidity at height 75 cm. A sensor (S5) was placed outside to keep track on the external conditions during the investigation. Sensors S1-S5 were battery-driven Hobo loggers from Onset. A thermal camera (FLIR C2) was used to take pictures of the ceiling in order to identify potential temperature differences and radiant discomfort.

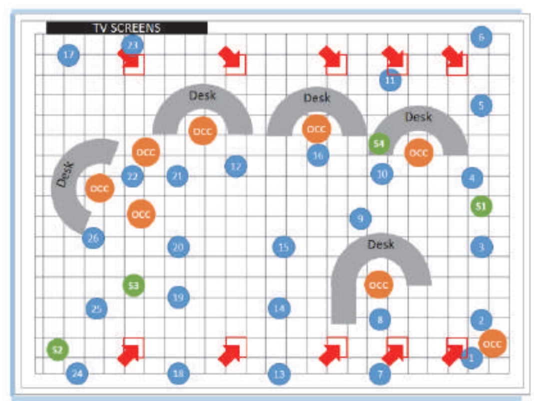

Fig. 2- Position of sensors, occupants and extractions

Fig. 2 depicts the floor plan of the room. The grey shapes represent the desks, the red arrows show the extraction outlets and the black rectangle is the wall of TV screens.

2.3 Evaluation

The results were compared to the indoor comfort criteria of EN ISO 7730 [8], which are summarized in Tab. 1.

Tab. 1 - Comfort categories as in ISO 7730

Cat.	Draught rate (DR)	Vertical temperature gradient	Vertical temp. difference, head-ankles
A	< 10 %	< 3 K/m	< 2K
B	< 20 %	< 5 K/m	< 3K
C	< 30 %	< 10 K/m	< 4K

The draught rate (DR) is calculated according to equation (1). It defines the expected percentage of people feeling uncomfortable because of the draught in the room. T_a is air temperature (°C), V_0 is mean air speed (m/s) and I_0 is the turbulence intensity (-).

$$DR = (34 - T_a)(V_0 - 0.05)^{0.62}(37.I_0\,V_0 + 3.14) \quad (1)$$

The air diffusion performance index ADPI was formulated to rate the indoor environment in rooms as a result of the air diffusion performance of the installed diffusers. It is described in ASHRAE Standard 113, 2005 [9]. The ADPI is defined as the percent of test points in the room where the effective draft temperature, θ and mean velocity, V_m, meet the criteria: -1.7 °C < θ < 1.1 °C and V_m < 0.35 m/s. These criteria are defined under the assumption that sedentary occupants will be comfortable. The effective temperature θ is defined in equation (2):

$$\theta = T - T_{ar} - 8(V_m - 0.15) \quad (2)$$

where T is the temperature at the measurement point and T_{ar} is the average room air temperature (°C).

Finally, the results were compared to literature by means of a q-T design chart.

3. Results and discussions

This section presents the results in the following order: plenum temperatures, vertical temperature gradient and radiant temperatures and then mapping of airspeeds, temperatures and draught rates in the room and in the proximity of the occupants.

3.1 Plenum temperature and relative humidity

The plenum is around 165 m^2 and substantial pre-heating of the ventilation air is expected in the plenum [2]. This pre-heating allows to supply colder air in the plenum without creating discomfort in the room. The supplied air increases its temperature by absorbing heat transferred from the room. Fig. 3 depicts the evolution of the temperature across the plenum; over the whole experiment, there was an average of 1.5 ˚C difference between the 2 sensors placed in the plenum. Given the airflow rate, the ventilation air absorbs approx. 28 W/m^2 through the ceiling or approx. 50% of the total cooling supply.

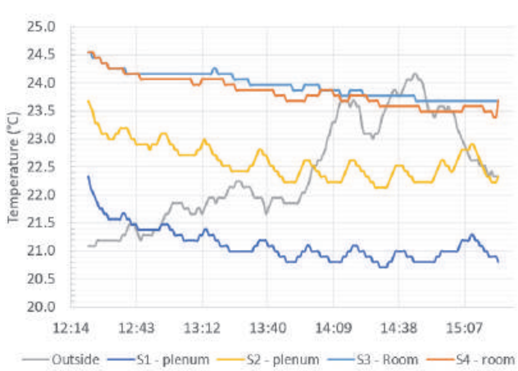

Fig. 3 - Temperature outside and in the plenum during test day

While the surface temperature is even in most of the room, the corners above position 1 and 6 are significantly colder as illustrated by the thermos-photos in Fig. 4, but this is probably due to the impinging jets of the old ventilation system in the plenum. From Fig. 1 it is clear, that the dynamic pressure of these jets are converted to high static pressure in the corners causing higher airflow in the corners.

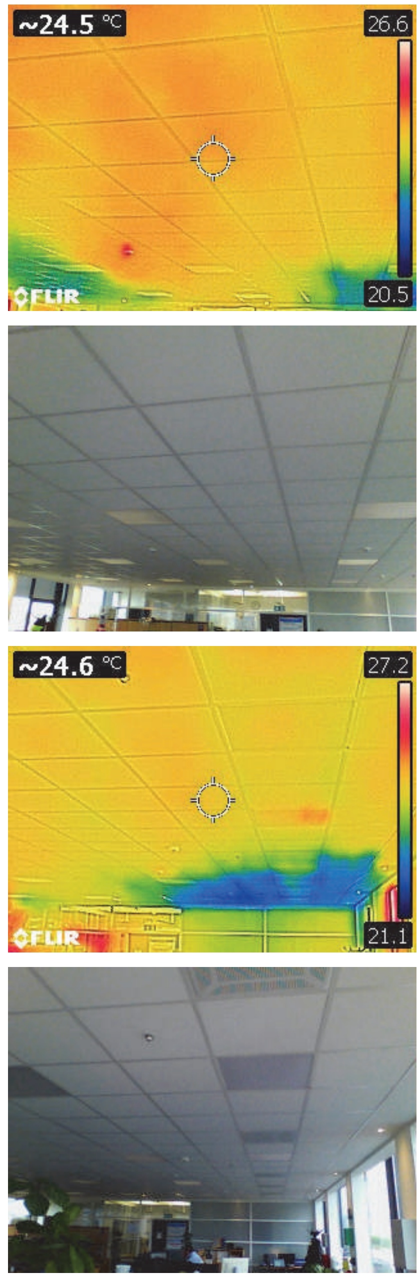

Fig. 4 - Thermal pictures of the ceiling

The relative humidity in the plenum is very stable with a 5% difference between the measurement at the inlet and the measurement at the opposite corner of the plenum. There does not seem to be any condensation or humidity rise in the plenum due to the dehumidification of the recirculation air in the cooling coil.

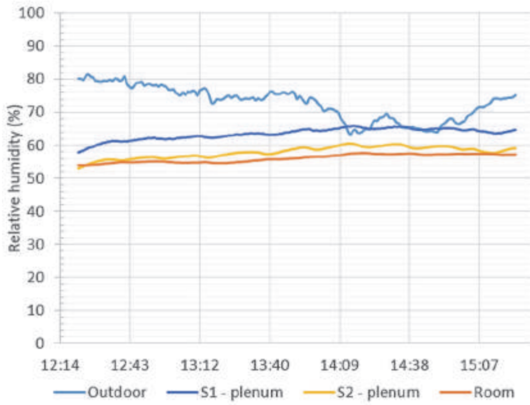

Fig. 5 - Relative humidity during the experiment

3.2 Vertical temperature gradient

The average temperatures for all the measurements are presented in Fig. 6. The temperature in the room is very even during the time of the measurements. The standard deviation is lower than 0.7 ˚C at every height and the temperature gradient per meter is below 0.8 ˚C everywhere in the control room and 0.34 ˚C on average.

Except for three positions, the temperatures are between 23 ˚C and 25 ˚C in the room. The differences come mainly from the different heights of measurements. It is also noticeable that the largest temperature difference (2 ˚C) occurs at the highest point of measurement (measured at 2.4 m in a room of 2.75 m height, so very close to the ceiling).

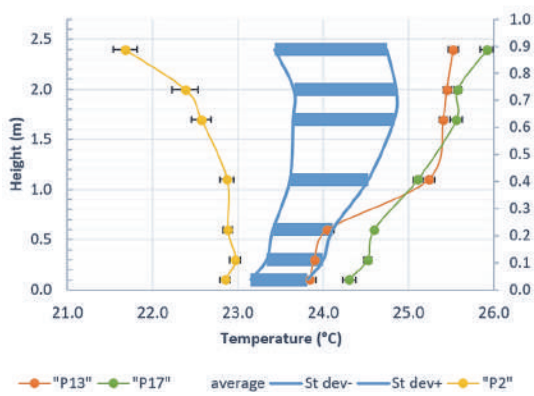

Fig. 6 - Vertical temperature gradient. The blue area represents the average temperature ± standard deviation

The three most extreme positions are still within the reasonable range of temperature. Position 17, placed next to the screen wall in the room, reaches slightly higher temperatures at the highest point, but still below 26 ˚C. The results in position 2 are the coldest. This is probably due to impinging jets of the old ventilation system in the plenum. Position 13 is located next to the windows and an extraction.

3.3 Air speed

The airspeed measured were on average between 0.10 and 0.17 m/s. Fig. 8 maps the airspeeds at four different heights. The figure illustrates that the highest airspeeds were below the ceiling and at ankle height. It also shows the high airspeeds below point 2. On a general level, 0.2 m/s is usually regarded as the threshold for draught and in this case, the airspeed exceeded 0.2 m/s in less than 9 % of the measurements.

The research literature shows that with diffuse ceiling ventilation, the dominant flow is created by the heat loads and that their power and distribution have an impact on the draught [4]. Considering the location of heat sources and the distribution of airspeeds at ankle height, a room size counter-clockwise vortex is probably mixing the air. Consequently, it is very important to measure the airspeeds in the proximity of the occupants. The results showed that the airspeeds were between 0.1 and 0.2 m/s from floor to ceiling, which is very slow considering the air change rate in the room. Another parameter that influences the draught in the room is the height. In the facility, the height was under 3 m and therefore was not problematic [10].

3.4 Draught rate

Fig. 7 below shows the draught rate around the occupants. The highest air speed observed was at the ankle level as a result of the room-size vortex.

Almost all the measurements have a DR below 20% and 71% of them have a DR below 10%. The lowest DR are usually found between 0.6 m and 1.7 m. As observed previously, the highest airspeeds are around ankle level and above the comfort zone. According to ISO 7730, the comfort level regarding the Draught Rate is Class B since it is below 20% everywhere (Tab. 2).

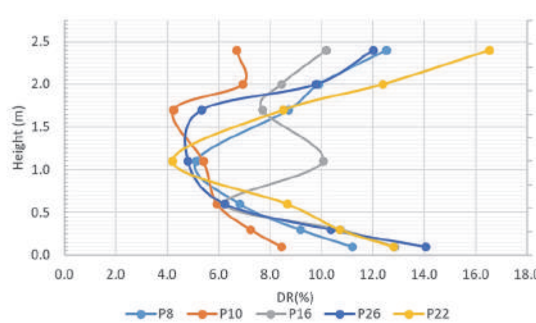

Fig. 7 - Draught rate in the proximity of the occupants

Tab. 2 - Overall results of the draught rates

Measurement points	Total: 182	%
DR < 20%	179	98.3%
DR < 10%	130	71.4%

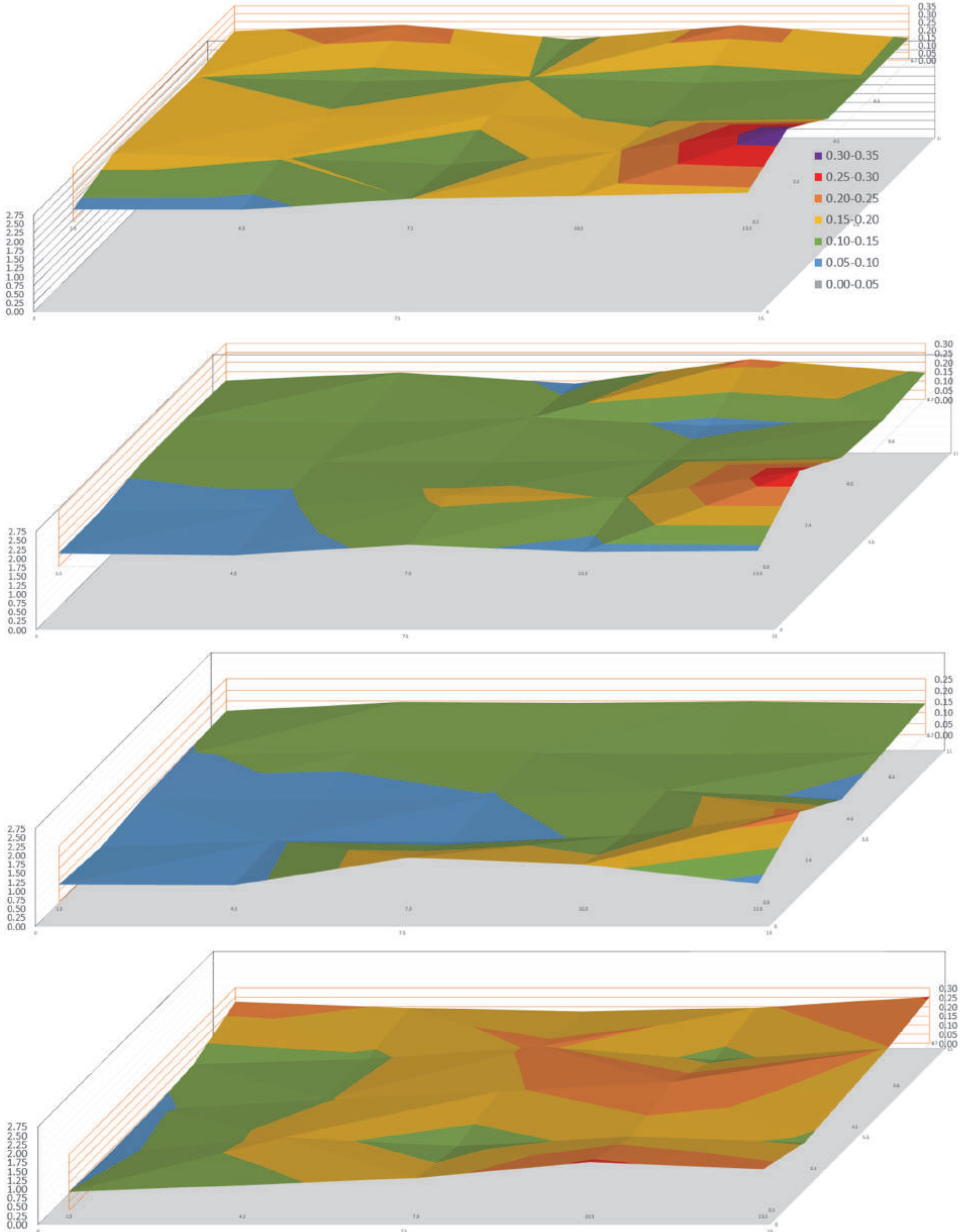

Fig. 8 - Air speeds at four different heights (2.4m, 1.7m, 0.6m, 0.1m). The map shows that airspeeds are highest below the ceiling (2.4 m) and at ankle height (0.1 m)

3.5 Air diffusion performance

In general, high ADPI is desired as it indicates a high level of comfort and good air mixing. The air diffusion performance index was 84% (Tab. 3), which is on par with many alternative overhead air diffusers at cooling load of 50 W/m2 [11]. The field mapping of velocities and temperatures was made with horizontal and vertical resolution as high as was practically possible, however, the ADPI index should be used carefully, because it may be influenced by furniture layout, location of heat sources and pollution sources.

Tab. 3 - Overall results of the draught rates

Measurement points	Total: 182	%
-1.7 °C $< \theta <$ 1.1 °C	153	84.1%
V_m < 0.35 m/s	182	

3.6 Occupant satisfaction

We did not conduct a formal survey as the number of users in the room is quite small, on an anecdotal basis, the occupants were very satisfied with the solution mainly because there were no high temperatures in the room any more as there used to be before the renovation. The occupants *were* asked if they could feel any draught and none of them reported any discomfort of any kind. The noise from the ventilation was audible next to the entrance, just below the inlet in the plenum but the level was reasonable and it was not close to the working places.

3.7 Other air supply options

There are many ways to supply ventilation air to the space. Rehva Guidebook 01 [7] provides some guidelines for the options: mixing and displacement. Using these guidelines on the airflow rate per floor area and the needed cooling capacity per floor area, displacement ventilation is recommended.

Displacement ventilation creates thermal stratification which can be exploited to reduce the airflow rate, because heat and pollution is concentrated in the upper zone. Assuming 20% lower airflow rate, divided between four corner diffuser units, Rehva Guidebook 01 recommends a unit of 1.2 m high with an adjacent zone length of 8 meters. With expected under temperature of 3K the system provides approximately the needed cooling. But it is clear from the room dimensions in Fig. 2 that adjacent zones would be difficult to keep free of occupancy in the office space and that the risk of draught therefore is high. Alternatively, radial ceiling diffusers could be an option. Each diffuser supplies 575 m3/h, which means 16 diffusers are necessary in a 4x4 pattern. Each diffuser has a throw length of approx. 3-4 m from the datasheet. Considering the throw length and the risk of jets colliding and being diverted into the occupied zone, it is very difficult to fit 16 diffusers into the space without creating a high risk of draught.

These results match the literature. Fig. 9 depicts a q-T design chart adapted from Nielsen [5] and Zukowska-Tejsen [6] that relates displacement diffusers and radial ceiling diffusers with diffuse ceiling ventilation. The result of this study is marked with an X and supports the dashed extrapolation on diffuse ventilation that Zukowska-Tejsen suggested.

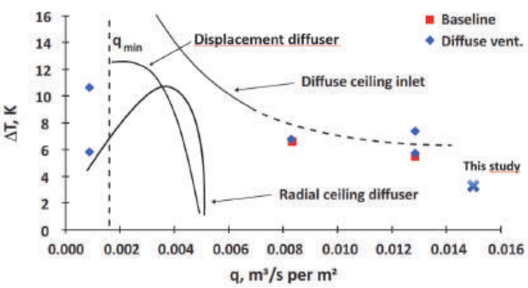

Fig. 9 – Design chart. Adapted from [5, 6].

4. Conclusion

In the plenum the difference of temperature was 1.5 ˚C between the inlet (supposedly the coolest point) and the opposite corner (supposedly the warmest point). The measurements showed an even distribution of the temperature everywhere in the room with measurements between 23 and 26 ˚C and an average vertical temperature gradient of 0.34 ˚C/m (max 0.8 ˚C/m). The infrared camera did not disclose significant radiant discomfort in the room.

The hygrometry in the plenum was also even and not close to the dew point so there was no risk of condensation that could cause damages to the ceiling tiles for instance.

The airspeeds were on average between 0.10 m/s and 0.17 m/s with the highest values at the ankle level as previously shown in different studies on diffuse ceiling ventilation. 71% of the logged points had Draught Rates (DR) below 10% and all positions were below 20% except one (position 2). The airspeed exceeded 0.2 m/s in less than 9 % of the measurements. The ADPI index showed performance on par with other overhead air diffusers.

As concluding remarks, the field mapping did not disclose zones with problematic high airspeeds and it was possible to keep a comfortable level, despite the high air change rate of 20 h^{-1}. Delivering the same amount of ventilation with displacement or swirl diffusers would have restricted the occupiable space significantly.

Data statement

The datasets generated during and/or analysed during the current study are not publicly available because the detailed data is owned by the client but will be available upon request.

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