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# Integrated design approach for improving personal summer thermal comfort in existing office buildings with suspended ceilings

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## **Abstract**

*Although most familiar in tropical climates and in Southern Europe, ceiling fans are also able to improve summer comfort in building interiors in Central Europe. This is mainly achieved by improved air movement near occupants. The paper reports on initial experimental results on a new ceiling fan concept for office environments, especially for existing buildings with summer thermal comfort deficits. Small low power fans are integrated into a typical, grid structured suspended ceiling, directly above each individual work place. The investigations cover comfort and acoustic measurements as well as simulations. The results underline the basic functionality of the design, improved thermal comfort and positive user feedback. Further investigations will address an enhanced concept in combination with night ventilation.*

***Keywords - thermal comfort, overheating, passive cooling, ceiling fan, measurements, user satisfaction***

## **1. Introduction**

Suspended ceilings are widespread in commercial buildings in Europe, especially in offices. Beside the advantages with respect to room acoustics and cladding of technical installations the major disadvantage is the reduction of the thermal capacity of the room. A lack of thermal capacity and night ventilation capabilities are typical reasons for high summer temperature peaks in the absence of cooling devices. The hot summers of 2003, 2006 and 2015 and the predicted climate change with its anticipated temperature increase as well as intensive heat waves have strengthened interest in summer thermal comfort in existing office buildings.

A typical measure known in Southern Europe is the application of ceiling fans. The fans offer a technically simple, inexpensive and, above all, effective method to increase air movement and thus thermal comfort in critical rooms of existing buildings. The effects are described already within several papers [1,2] and thermal comfort standards such as DIN EN ISO 7730-2006, DIN EN 15251-2007. On the other hand classical ceiling fans are designed to address more than one workplace thereby creating conflicts

between individual preferences related to air velocity. Own investigations of classical ceiling fans were addressed in [3,4].

## 2. Suspended Ceilings Advantage: Improved Room Acoustics

Acoustic absorbers within a suspended ceiling increase the reverberation time thereby reducing the noise level in open floor plan offices. This typically affects the middle and higher frequencies due to the absorbing characteristics of conventional panels (figure 1). The unacceptable conditions in a room without acoustic panels mark the opposite to the intensive attenuation with the a fully suspended ceiling. Reducing the number of acoustic panels to 16% of the ceiling surface and covering the other ceiling parts with metal meshes still allows acceptable conditions and positive user feedback. The relatively good result is caused by the additional effect of the backside of the panels, when only parts of the ceiling are equipped.

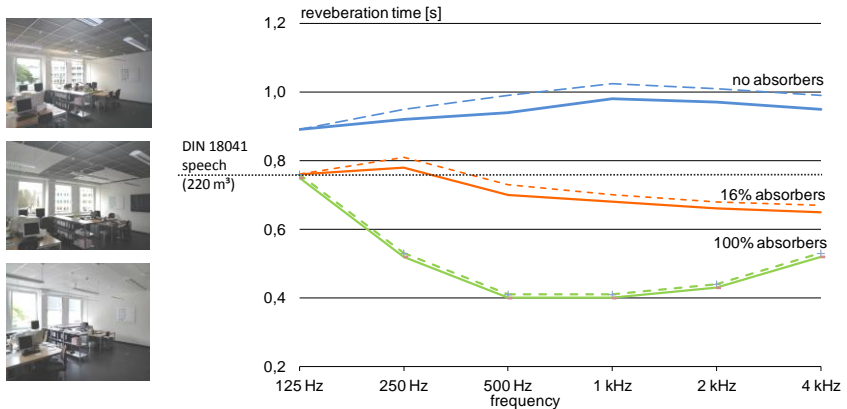


Fig. 1 Measured reverberation times of an 57 m<sup>2</sup> open floor plan office room with different configurations of the suspended ceiling: fully suspended with acoustic panels, 9.4 m<sup>2</sup> (16%) acoustic panels only, no acoustic panels. The dotted lines indicate the non occupied room, the massive lines the room occupied with 4 persons. The horizontal line indicates the needs according to the standard DIN 18041 (speech).

## 3. Suspended Ceilings Drawback: Lack of Thermal Mass

Suspended ceilings insulate the thermal mass of the ceiling from the indoor air due to the low thermal conductivity of the acoustic panels and the air layer above. This results in slightly higher peaks in summer indoor air temperatures but faster decreasing temperatures after hot periods. Simple forms of night ventilation such as tilted windows increase the nocturnal heat

extraction in periods with low or moderate ambient temperatures, thereby decreasing the indoor temperatures. Simulation results (figure 2) underline this theory. Practical experiences show, that the effect of night ventilation is less than predicted by simple single zone modeling. The reasons behind are the inhomogeneous temperature distribution at the ceiling and the temperature rise of the air passing from the inlet to the outlet: Heat extraction from the ceiling is maximized near to the facade and continuously decreases to the room depth due to decreasing temperature gradients.

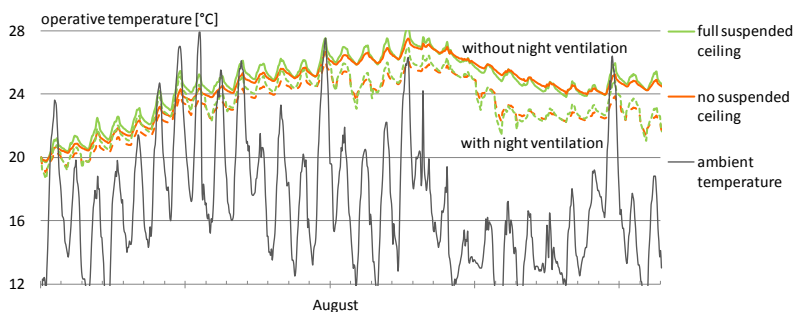


Fig. 2 Transient temperature development for the occupied open floor plan office according to figure 1 simulated with and without suspended ceiling as well as with and without night ventilation (2 ac/h, 10 pm to 6 am). Simulation performed with a 1 or 2 zone model (room, space between ceiling and acoustic panels) by WUFI Plus 3.03 and Essen TRY.

#### 4. Concept Development: Ceiling Integrated, Personal Fans

The new concept investigated and described in the paper is based on small ( $\varnothing$  300 mm), individual fans as integrated part of the suspended ceiling section directly above each workplace. The fans are placed within a standard acoustic panel of 62.6 x 62.5 cm of a grid type suspended ceiling. They are designed to create a circulation air flow rate of up to 115 m<sup>3</sup>/h by sucking air from the site of the acoustic ceiling along the ceiling and deflating the air vertically down from the ceiling. The air supply to the fan is created by modifying a large part of the suspended ceiling segments from acoustic panels to expanded metal meshes while still keeping acoustic panels above the work places (figure 3). Each fan can be controlled individually with variable flow rate by an app on the work place computer.

The fan operation increases the air movement at the upper body level of a seated person in a radius of about 20 cm to 0.3-0.5 m/s. The velocity decreases drastically with the distance from the fan centre allowing for almost no interaction with the person seated on the opposite (figure 4). Due

to efficient DC motor technology the power to run a single fan like this is just 6.5 W for 115 m<sup>3</sup>/h air flow. The resulting specific fan power is measured to 0.06 W/(m<sup>3</sup>/h) thereby increasing the air temperature by only 0.15 K due to the motor waste heat. Fan and motor technology are much more efficient compared to standard ceiling fans on the market [5].

A critical point may be the noise penetration from the fans. The weighted and averaged sound level was measured to increase by about 10 dB<sub>a</sub> (=doubling). As the level increases from low 26 to 36 dB<sub>a</sub> this was still rated as acceptable by the occupants. A hygienically critical point is the possible sucking of dust from above the suspended ceiling into the air supply to the work place. This issue was not found to be relevant in practice although no special cleaning took place after many years of room utilization with closed suspended ceiling before starting the experiment.

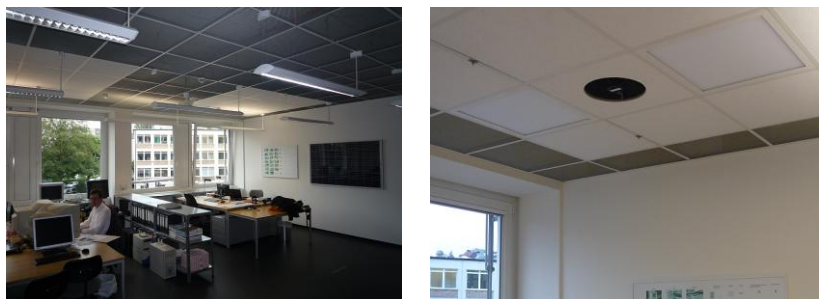


Fig. 3 Pictures of the room (left) and the fan integration in a typical acoustic panel of the suspended ceiling section (right). The major part of the ceiling is now equipped with porous metal meshes as shown on the left picture. A section with acoustic panels remains above the work places to hold the fan combined with two flat LED light panels.

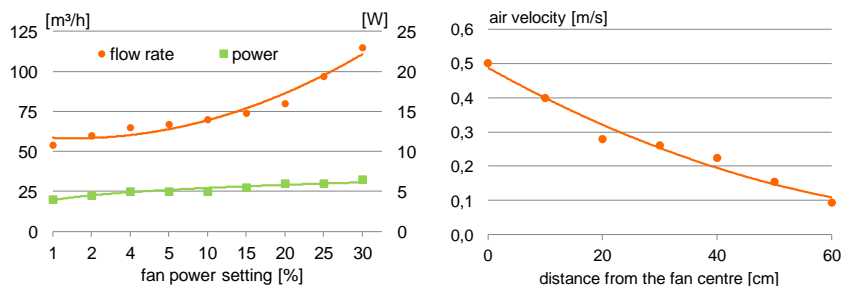


Fig. 4 Typical fan characteristic measured (left). The resulting work place air velocity (right) was measured at 130 cm above the floor (head of a seated person), 165 cm under the fan at power setting 30%.

## 5. Experimental Application: Comfort Measurements

Indoor climate measurements were performed in summer 2015 at Wuppertal University Campus Haspel in the open floor plan office shown in figure 3. The 57 m<sup>2</sup> office was occupied with three persons. The south-west facade with double glazed windows is shaded by external, translucent screens, operated manually. Windows were opened manually and partly left tilted over night. No special instructions were made to the occupants. Figure 5 illustrate the ambient temperature conditions. Reflecting the worldwide hottest year since continuous meteorological recordings are established, the temperature level was much higher, compared to usual summers (as used for the simulations shown with figure 2).

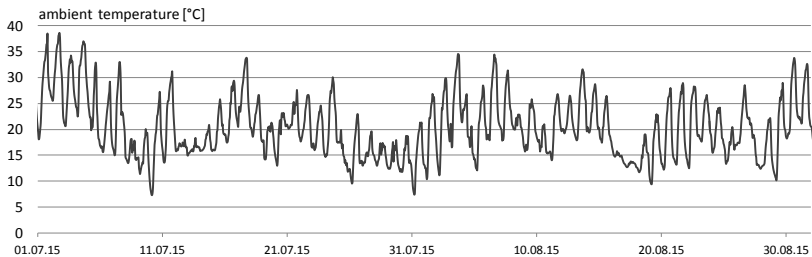


Fig. 5 Ambient temperature conditions at Wuppertal, Germany within July and August 2015 based on hourly averaged data.

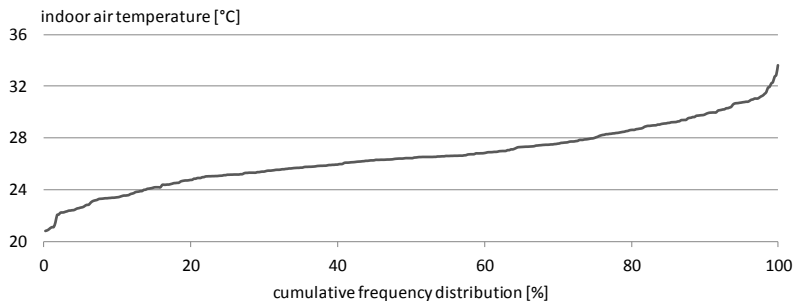


Fig. 6 Cumulative frequency distribution of the measured indoor air temperature within July and August 2015 based on hourly averaged data for all working hours (8 am to 6 pm, workdays only).

All comfort parameters (air temperature, air velocity, radiant temperature, rel. humidity, refer to the picture in figure 7) were continuously recorded with 5 min resolution from beginning of July to end of August at one unoccupied work place opposite of an occupied place. Figure 6 illustrates the cumulative frequency distribution of the indoor air temperature at work place level. Due to the extreme weather conditions, temperatures above 28°C occur in about 30% of the total period. Indoor humidity data were recorded between 30% and 60% with an average of 44%.

Based on the data the predicted mean vote (PMV) was calculated according to the formula given in DIN EN ISO 7730 - 2006 (figure 7). The metabolic rate was assumed to 70 W (relaxed seated) and the clothing rate to 0.5 clo (light summer clothing). The average PMV during the typical times of work was reduced from 0.94 to 0.45 by use of the fan (vertical line in figure 7, average indoor temperature 27°C). According to DIN EN ISO 7730 an increase in air velocity of 0.5 m/s correlates to an increase of the acceptable room temperature by 1.7 K. This significantly extends the comfort zone in a non actively cooled building.

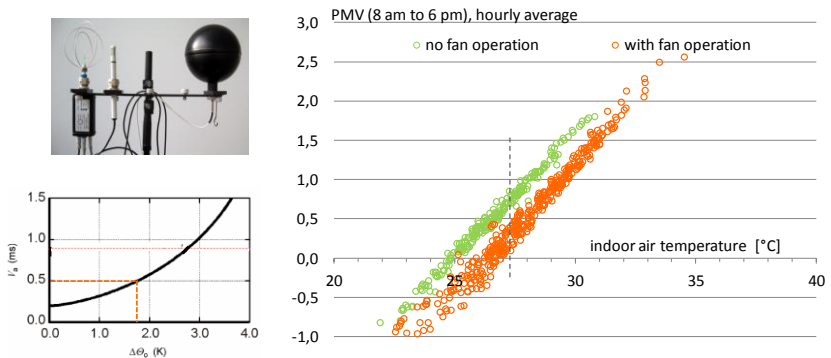


Fig. 7 Calculated hourly PMV data based on two month of measuring air temperature, air velocity, radiant temperature and relative humidity on a work place in the room shown in figure 3. Data are separated for times with and without fan operation. The metabolic rate was assumed constant to 70 W, the clothing rate to 0.5 clo. The small figures on the left illustrate the monitoring equipment and the relation between air velocity and increase of the acceptable room temperature according to DIN EN ISO 7730.

## 6. Conclusions and Outlook

The generally high temperature level in the office room reflects typical conditions in existing buildings with solar exposed facades in Germany. The measurements underline the need for improvements such as more efficient shading, activation of thermal mass and night ventilation as well as a more consequent user behaviour and/or system automation. Hot summers such as 2015 increase the thermal stress and decrease the user satisfaction.

The proposed ceiling fans in combination with the modification of the suspended ceiling have demonstrated a further element of user intervention with the advantage of decentralise application in rooms with high thermal stress. The positive user response was stimulated by the immediately positive thermal effect (no time lack), the conformability of the function and the possibility of individual operation.

On the other hand users may expect fresh air supply by the fans but only circulation air is provided. This may change their window ventilation behaviour. The misunderstanding should be considered within a modified design.

Due to efficient motor and fan technology the additional electric energy demand for operating the personal fan is small and predicted to 3.1 kWh per person or 0.26 kWh/m<sup>2</sup>a (8 h per day, 60 day per year, 12 m<sup>2</sup> person).

Further work focuses on the integration of the ceiling fans into an improved night ventilation concept. The fans may be automatically operated during night to increase the convective heat transfer at the ceiling and to stimulate a more homogeneous temperature distribution in the room, especially in the room depth [3]. This may allow for a more efficient night ventilation at relatively low air change rates compared to an increased air change rate. High air change rates are not easy to achieve in existing buildings in the absence of typical structural configurations such as atria.

Another focus of research are the user preferences with respect to options for manual interventions such as shading, window ventilation or fan operation at rising indoor temperatures [4]. The fans increase the number of possible interventions. Studies will be performed to clarify the ranking of inventions at rising temperatures.

Due to the limitations of the Fanger comfort model to analyse thermal comfort at high air velocities, the studies will be extended to the so called standard effective temperature (SET) proposed by Gagge et. al. 1986 [6,7].



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