EXPERIMENTAL STUDY OF DIFFUSE CEILING VENTILATION IN A CLASSROOM

Christian Anker Hviid[1], Søren Terkildsen[*1]

1 Tech.Univ. of Denmark, Dept. of Civil Engineering
Brovej, building 118
DK-2800 Kgs. Lyngby, Denmark
**Corresponding author: sterk@byg.dtu.dk*

ABSTRACT

Diffuse ceiling ventilation is a novel air distribution device that combines the suspended acoustic ceiling with ventilation supply. A diffuse ceiling distributes the supply air above the acoustic tiles and has proven performance in laboratory experiments. To study the performance in real conditions a classroom was retrofitted with mechanical ventilation and a diffuse ceiling. The employed ceiling comprises active panels penetrable to air and impenetrable passive panels. The performance was studied with regard to air movements, temperatures and air change efficiency at two different air changes. The experiments were carried out during class to obtain realistic conditions. At both airflows did the ceiling perform satisfactorily with air movements and temperatures within the requirements of indoor climate standards. The air change efficiency is comparable to conventional mixing ventilation.

KEYWORDS

Diffuse ceiling ventilation, ventilation efficiency, ventilation, draught rating, tracer gas

INTRODUCTION

School classrooms are characterized by high occupancy and high thermal load. Consequently high ventilation rates are required which can be difficult to fulfil with conventional inlet diffusers without causing draught

Development of new concepts to ventilate school classrooms is therefore relevant and one promising solution is diffuse ventilation air inlet. The concept is commonly used in live stock buildings [1] and in the clean room industry [2], yet it is increasingly employed in comfort ventilation. The principle of diffuse air inlet in comfort ventilation is to inject the supply air into a pressure chamber above a standard suspended acoustic ceiling. The air is distributed to the room below through cracks and perforations. The flow velocity is very small and irregular, hence the term diffuse.

The reported research in this area mostly relies on laboratory experiments where results have been promising. In [3] diffuse ceiling ventilation outperformed five conventional air distribution systems in a laboratory office environment. The findings were supported by [4] who carried out experiments in a test facility resembling a small classroom. Tracer gas experiments showed that diffuse ventilation inlet provided perfect mixing, while air temperature and air velocity measurements did not disclose any local discomfort in the occupied zone over a broad range of flow rates and inlet temperatures. Similar draught assessments in a class room laboratory setup is reported by [5], who, in the same paper, also report a pilot study in a real classroom. However, the measurements only included overall CO2-concentration and a questionnaire about perceived air quality and not quantifiable measurements of air temperature and velocity or air quality.

To investigate the performance of diffuse ceiling inlet under real conditions a diffuse ceiling was installed in a classroom at Vallensbæk primary school. The investigation encompassed several elements to document the thermal comfort and to map the air distribution in a class room with diffuse ventilation air inlet, including: local comfort by air temperature and air velocity, air change efficiency, and radiant asymmetry. The objective was to validate how diffuse ceiling inlet performs in practise and to document the applicability of diffuse ceiling ventilation in classrooms.

METHODS

Room description

A classrooms at Vallensbæk primary school was refurbished with a new mechanical ventilation system including a new suspended acoustic ceiling functioning as diffuse ceiling inlets. Vallensbæk School has outer masonry walls and partitions of gypsum. The floor is a concrete deck with linoleum covering and the ceiling is a wooden roof structure, see Figure 1. The ceiling was suspended 0.2 m from the roof structure to create a plenum to distribute the air and resulted in a floor height of 2.5 m in the main part of the room.

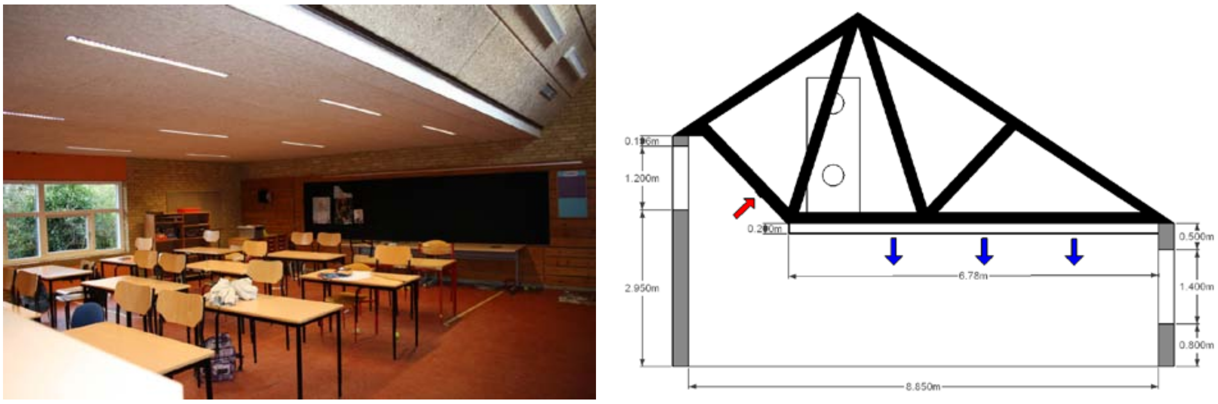

Figure 1. Left: Picture of classroom where measurements were performed, Right: Schematic of classroom with dimensions and principle of air distribution (blue arrows inlet, red arrows exhaust).

The floor area was 9.15x8.85 m, see Figure 3 and the windows on the main facade is oriented North-West, the solar gain during the occupied hours is therefore limited and only fabric curtains are installed as shading device. The classroom is usually occupied by 24 pupils in 6th grade (age 11-12).

Diffuse ceiling layout

The ventilation ceiling consists of a metal frame suspension system to create the plenum on which cement bonded wood-wool panels were mounted. This is a commonly used product in Danish classrooms for its acoustic properties. For use as a diffuse ventilation inlet, two types of panels are needed : active and passive. The active panels are permeable so the supply air can penetrate and passive panels has 20 mm of hard painted mineral wool glued to the backside making them non-permeable, see Figure 2. The mineral wool improves the acoustic properties and permits control of the supply air distribution in the room. A small overpressure is created in plenum above the panels that ensures the supply air is equally distributed through the active panels. In the room 6 active panels were used and placed as shown in Figure 3 equalling an area of 8.6 m^2. The panels were not uniformly placed as intended but this was discovered after the measurements were performed.

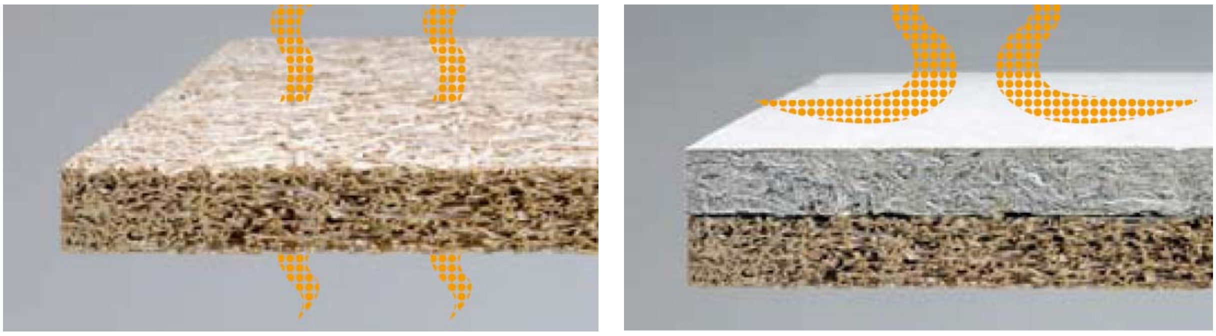

Figure 2. Left: Active plate of cement bonded wood-wool, Right: Passive plate has a layer of impenetrable mineral wool. Source: www.troldtekt.dk

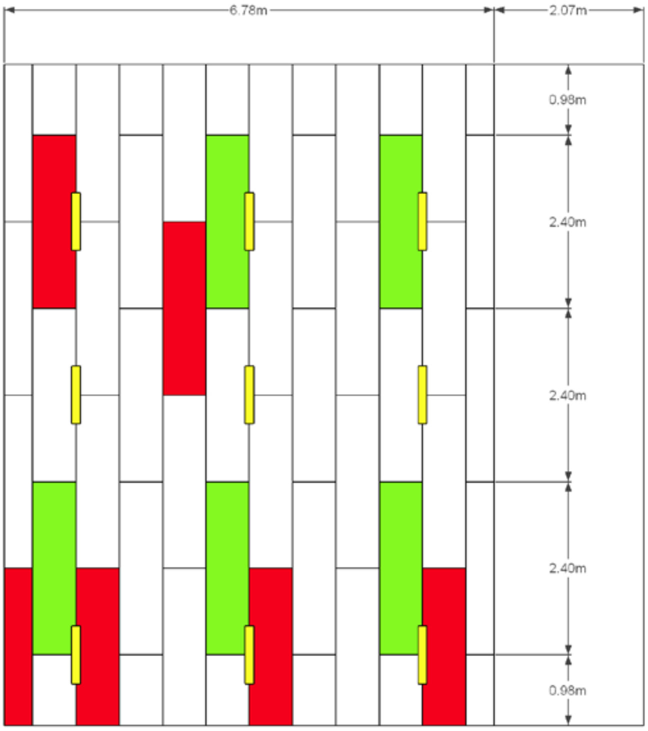

Figure 3. Placements of active cement bonded wood wool panels (red) and passive panels (white), green indicate the intended placement of the active panels.

The fresh air inlet was placed slightly off-centre of the suspended ceiling, blowing vertically down against a passive panels thereby distributing the air uniformly in the pressure chamber. The outlet air was extracted via existing diffusers located on the sloped part of the ceiling, see Figure 1. The supply and extract flow rate was balanced and controlled by dampers. The lighting fixtures were integrated in the ceiling for design reasons and to avoid vandalism, see Figure 1. The embedding of lighting fixtures caused leaks in the ceiling in addition to the active supply panels.

MEASUREMENTS

Four scenarios of measurements were performed at airflow rates of 500 m^3/h and 1000 m^3/h and inlet temperatures of 10 and 17 ^{0}C as stated in Table 1. The airflows correspond approximately to indoor environment category 3 and 1 in the European Standard 15251.

During the measurements 21 out of 24 pupils were present and one radiator below the windows where on and had a temperature of 55 °C corresponding to a heat load of approximately 1100 W. The only other heat load in the room was the lighting system 9x2x18 W.

	Supply flow	**Air change**	**Air flow per pupil**	**Supply air temperature**	**Measurements**
Scenario 1	500 m^3/h	2.45 h^{-1}	5.8 l/s	10 °C	Velocity, temperature
Scenario 2	500 m^3/h	2.45 h^{-1}	5.8 l/s	17 °C	Vel., temp., air change efficiency
Scenario 3	1000 m^3/h	4.90 h^{-1}	11.6 l/s	10 °C	Velocity, temperature
Scenario 4	1000 m^3/h	4.90 h^{-1}	11.6 l/s	17 °C	Vel., temp., air change efficiency

Table 1. Investigated ventilation scenarios.

Local air velocity and air temperature

Mixing ventilation is achieved by inducing air at relatively high velocity above the occupant zone. The entrainment of the jet causes supply air to be mixed with room air. Efficient mixing is therefore an indicator of turbulent flow patterns and discomfort by draught. In diffuse ceiling ventilation the supply air is induced into the room with relatively low air velocities limiting the risk of draught caused by the ventilation air inlet. Mixing is achived by the convective plumes of the occupants present. However, in [6] CFD simulations indicated that the thermal plumes force the supply air to regions with no heat sources, leading to cold downdraft and risk of draught in those regions.

Therefore air velocity and air temperature measurements were carried out with two Brüel og kjær Indoor Climate Analyzer model 1213, to examine the risk of discomfort due to air movements in the room. The accuracy of the temperature sensor is ±0.2 ^{0}C and the velocity sensor has an accuracy of ±0.1 m/s. The measurements were performed in 8 points evenly distributed and placed close to tables in the occupied zone of the room, marked with triangles in Figure 3.

At each point the air velocity and temperature was measured at heights of 0.1 m and 1.1 m corresponding to ankle and neck level of a sitting person as specified in CR1752 [7] and each measurement was averaged over 3 minutes.

According to (CR1752) maximum air velocities of 0.12, 0.15 and 0.18 m/s are allowed for indoor environment category A, B and C, respectively, and category B is used as reference to evaluate the measurements. The air temperature must be between 20-24 °C for winter conditions in category B which is applicable for the conditions under which the measurements was performed.

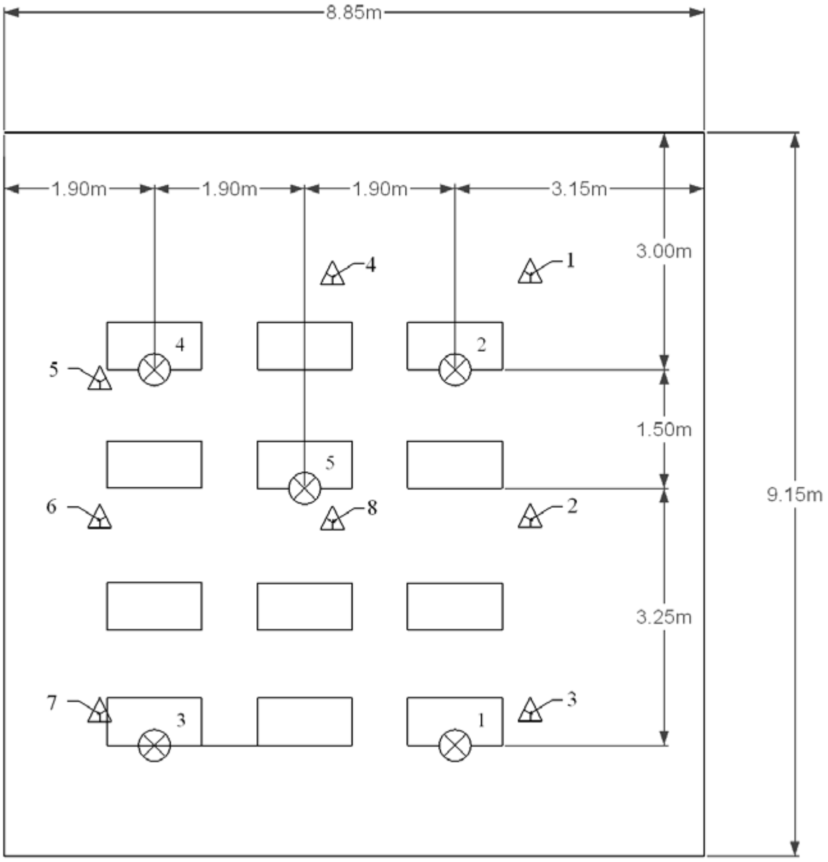

Figure 4. Location of measuring points in classrooms, triangles represent air temperature and –velocity measuring points and circles represent tracer gas measuring points.

Air change efficiency and local air change index

Air change efficiency ε^a is a measure of the average time it takes to replace the air in the room compared to the shortest possible air change time. It is the rati of the nominal time constant τ_n, and the actual air change time $\bar{\tau}_r$. The latter can be derived from the mean age of air concept [8].

$$\epsilon^a = \frac{\tau_n}{\bar{\tau}_r} \text{ x } 100\%$$

If the mixing of the supply air in a room is optimal the actual air change is twice the shortest possible time. Therefore full mixing has a maximum air change efficiency of 50 %. Lower efficiencies indicate incomplete mixing or short-circuited flow and higher efficiencies indicate flow regimes transitioning into displacement ventilation.

Local air change index represents the ratio of mean age in the exhaust and local mean age of air at the point of interest. At full mixing the age of air in the exhaust is the same as the age of air in the room and the ratio is equal 100 %.

Tracer gas

The concentration-decay method was used to determine the mean age of air. The equipment used was a photo-acoustic gas monitor model 1312 from Innova and a multipoint sampler and doser from Brüel & Kjær model 1303. The gas used was Freon R-134a that has a density of 4.25 kg/m^3, about 3.5 times higher than air. The multipoint sampler had 6 tube connections that were divided with five in the room and one in the extract duct. The five points chosen in the room were at each corner table in the occupied zone and at a table in the middle, all at a height of 1.1 m similar to the height of a sitting person. The points are marked with circles in Figure 4 and were chosen to give a representative picture of the mixing efficiency in the occupied zone and identify any stagnant zones. In the experiments the tracer gas was injected into the room until a constant concentration was reached and two swivel fans ensured fully mixing in the room. Depending on low and high airflow rate, a constant concentration of approximately 5 or 10 ppm was achieved, respectively, and the swivel fans were turned off and the following decay at the 6 sampling points was recorded. From this the local mean age of air in each point and the air change efficiency of the room were determined.

RESULTS AND DISCUSSION

Air velocities

The air velocity was measured at two heights, two flow rates and two supply temperatures. In Figure 5 and Figure 6 are shown the results for the supply temperature of 17 °C and 10 °C respectively. In the figures the mean air velocity over the sampling period of three minutes is shown as columns with an error bar displaying the standard deviation. The standard deviation shows that negative (physically invalid) air velocities has been recorded, especially for very low mean values. The standard deviation assumes Gaussian data distribution but this can be disturbed by outliers in the sampled data. These outliers are probably generated from turbulent flows caused by seated, yet active children during the measurements.

At both inlet temperatures the comfort threshold of 0.15 m/s is fulfilled except at point 3 and 7. Point 3 is located close to the leaky ceiling hatch and point 7 is located in the corner where, erroneously, two and not one active ventilation plate were installed.

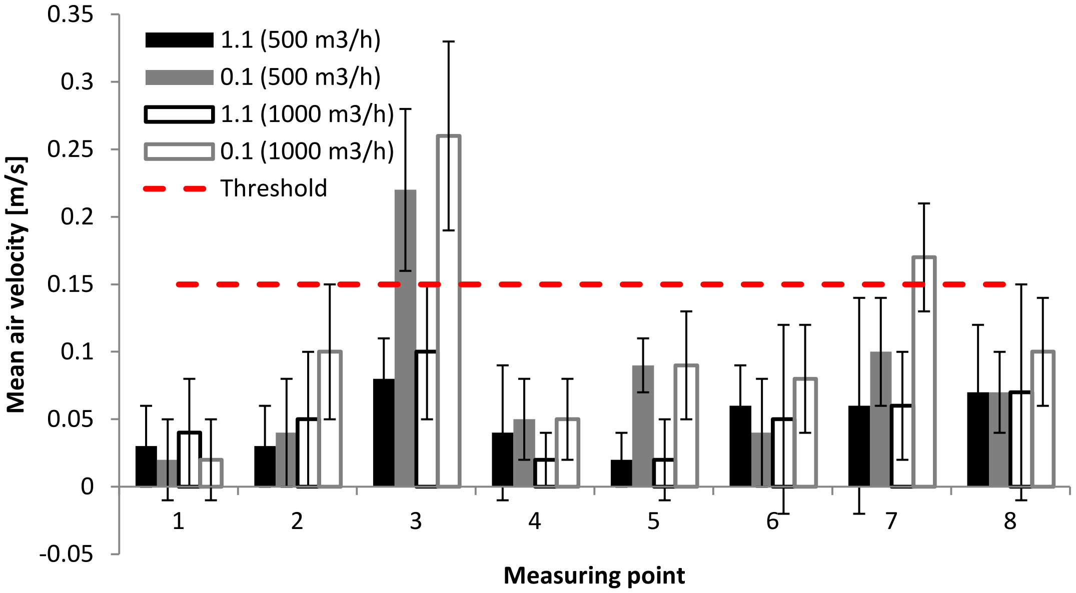

Figure 5. Measured air velocities at 0.1 and 1.1 m above the floor and flow rates of 500 and 1000 m^3/h with a supply temperature of 17 °C, scenario 2 and 4.

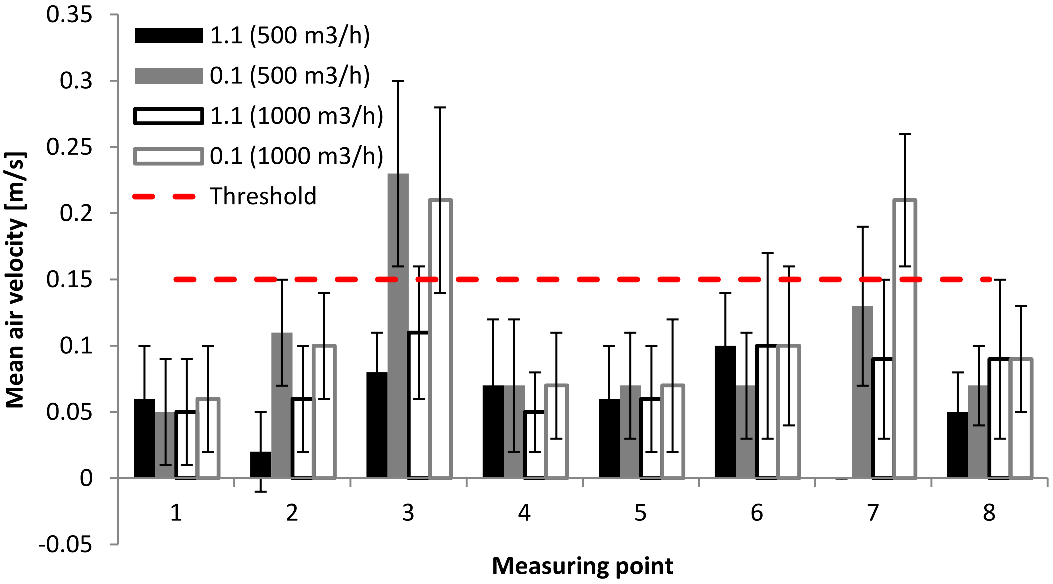

Figure 6. Measured air velocities at 0.1 and 1.1 m above the floor and flow rates of 500 and 1000 m^3/h with a supply temperature of 10 °C, scenario 1 and 3.

The measured air temperatures are shown in Figure 7 for an inlet temperature of 17 °C and Figure 8 for an inlet temperature of 10 °C. The results show that the air temperatures were quite uniform across the room, maximum 1 degree difference between the points when comparing the respective heights and flow rates measurements.

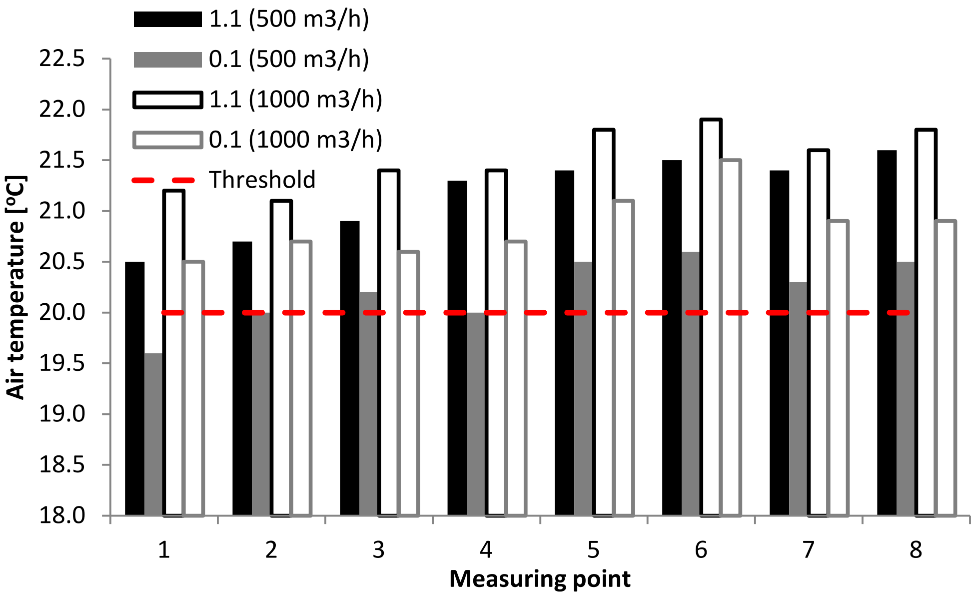

Figure 7. Measured air temperatures at 0.1 and 1.1 m above the floor and flow rates of 500 and 1000 m^3/h with a supply temperature of 17 degrees, scenario 2 and 4.

At the inlet temperature of 10 °C the air temperature measurements were below 20 °C at all points under the high flow rate and many points under the low flow rate. One radiator was malfunctioning and therefore the heating system was not able to compensate.

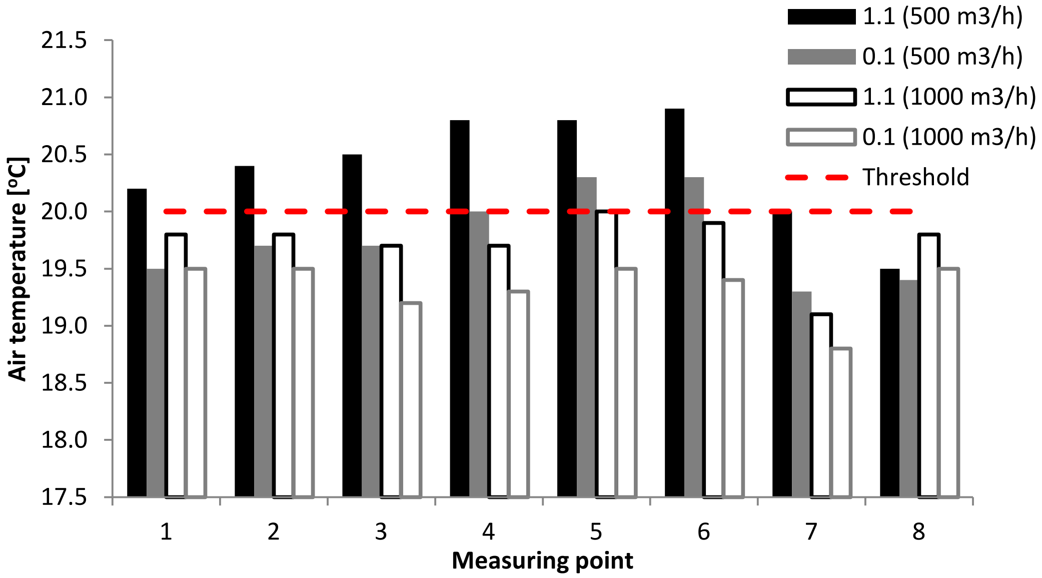

Figure 8. Measured air temperatures at 0.1 and 1.1 m above floor and flow rates of 500 and 1000 m^3/h with a supply temperature of 10 degrees, scenario 1 and 3.

Air change efficiency

In Figure 9 (left) is the local air change index of 5 sampling points in the classroom shown. The values are close to 100 % meaning similar air quality in all of the sampled points. The air change efficiency shown in Figure 9 (right) support the conclusion on room level, however, higher flow rates indicate transitional flow regimes into displacement ventilation which increases the risk of downdrafts.

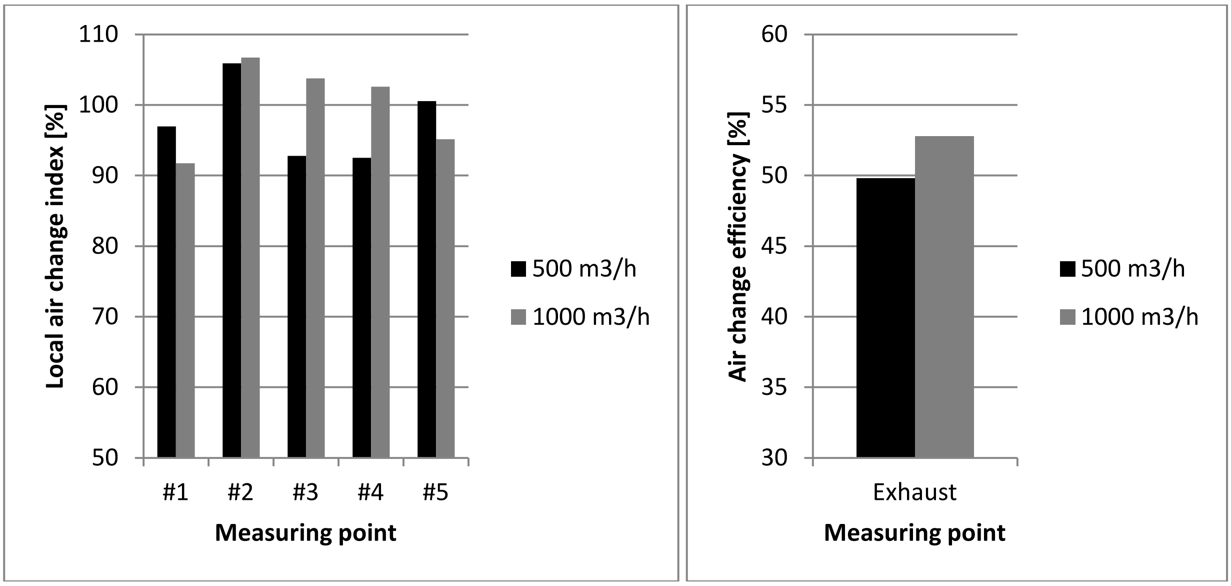

Figure 9. Left: Local air change index at sampling points. Right: Air change efficiency

Ceiling surface temperature

The infrared pictures in Figure 10 were taken with an inlet temperature of 10 °C to give a larger temperature difference and thereby clearer images.

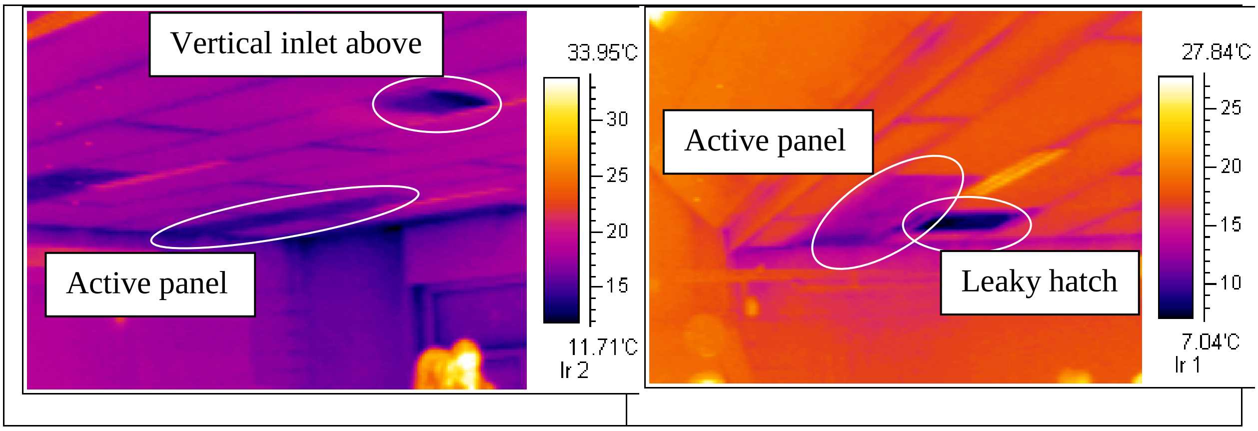

Figure 10. Infrared pictures of two corners with two different temperature coloring

The pictures clearly show that the active panels have a lower surface temperature than the passive panels. The temperature of the active panels is around 14 °C even though the supply air temperature is 10 °C. This shows preheating of the air when it passes the panels. This effect is due to radiation exchange of the ceiling with the rest of the room surfaces [6]. The panel joints are clearly visible due to the heat transmission of the metal suspension system. Most of ceiling has equal temperature with the room temperature and the radiant assymetry is deemed negligible.

CONCLUSION

The objective of the work in this paper was to validate the performance of diffuse ceiling ventilation in practise and document its applicability in school classrooms. Based on the investigation the following can be concluded on diffuse ceiling ventilation.

- The experimental results are in good agreement with previous results from test facilities and simulations.
- Virtually no risk of draught at low or high flow rates.
- Uniform airflow field with little difference between ankle and head height.
- Uniform temperature distribution with little difference between ankle and head height at both high and low flow rates.
- Negligible radiant asymmetry
- Perfect air mixing throughout the room independent of airflow rate.

Overall the results are positive and no negative aspects were detected. It is therefore concluded that diffuse ceiling ventilation in the studied form is applicable for use in school classrooms.

ACKNOWLEDGEMENTS

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