Effect of Air Distribution Methods on Classroom Air Quality

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SUMMARY
One of the main factors for inadequate indoor climate conditions in classrooms is the design of air distribution. This paper compares the indoor climate in the classroom in the summer and winter conditions with most commonly used mechanical air distribution systems. First the indoor climate of a half classroom is measured in a full-scale laboratory test by using several air distribution methods: wall supply air grilles, ceiling diffusers, perforated duct diffusers an displacement ventilation units. Half a classroom is then simulated with CFD, and finally the whole classroom is simulated.

Thermal comfort parameters and age of air distribution with different air distribution methods are also compared in the paper. Indoor climate in the occupied zone proved to be most optimal with displacement ventilation and ceiling diffusers. Air distribution with supply air grille gave uniform conditions, but this can cause problems due to too high velocities in some locations. Supply air jet from perforated duct diffuser and ceiling diffuser tend to be carried along thermal plumes from the heat loads.

IMPLICATIONS
Internal heat loads can have a significant effect to the air distribution, and therefore to the indoor climate. In this paper the effect has been evaluated with different air distribution arrangements, which provides essential information when designing effective classroom ventilation. Measurements were done in a controlled measurement chamber with calibrated sensors, and CFD simulations were compared to the measurement results. Uncertainty is discussed based on comparison of different methods.

INTRODUCTION
The indoor climate quality in schools has been found to be poor in a number of surveys (Daisey et. al 2003, Mendell et. al 2005). Poor indoor air quality causes an increase in symptoms and illnesses as well as shortening attention span, while good air quality can enhance children's concentration and teachers' productivity (Wargocki et. al 2005). The most common indoor climate problems are inadequate ventilation and thermal comfort. To achieve a good indoor climate, an adequate airflow should be used. The functionality of air distribution, including air change effectiveness, should be analysed to guarantee performance.

Carbon dioxide concentrations are often used to substitute the outdoor airflow rate per occupant, and indoor air quality in schools is primary evaluated by CO2- concentrations with many international standards recommend a maximum concentration level of 1000-1200 ppms. To fulfil this target, an airflow rate of about 6 l/s per person would be required. In this study IAQ is additional evaluated for effectiveness of local air change, or age of air, in different parts of the room by using CFD simulations.

The location and strength of heat gains have a significant effect on the air flow patterns (Kosonen et. al 2007). Thus when the air distribution strategy is designed, the functionality of air distribution should be analysed in different load conditions to guarantee optimal performance. The performance of four typical air distribution methods was studied first in a mock-up classroom, by measurements and then by CFD simulations of measured half classroom and finally of whole classroom. The main objective was to get a holistic view of the performance and differences between typical air distribution schemes in both winter and summer conditions using different occupancy ratios.

METHODS

The indoor climate of classroom shown in Fig 1 was tested in summer and winter conditions in full-scale tests and in CFD simulations. Heat balance in the test of the whole classroom modelled with CFD is described in Table 1. Mechanical air distribution units are shown in the Fig. 2: two wall supply air grilles are located in the wall opposite to the window, two displacement ventilation units in the corners at the teacher's end, and two ceiling diffusers and perforated duct diffusers in the middle of room perpendicular to the grilles. Four exhaust air valves are located equally in the ceiling near wall grilles.

First the indoor climate of classroom was measured by using full-scale laboratory test. This included approximately half of the typical classroom. The full-scale test results are published earlier by Kosonen and Mustakallio (2010). Tests were done in typical average conditions for summer and winter season in Finland. The summer test used full occupancy (cooling load of approx. 50 W/m2) and the winter test used half occupancy (heating demand of approx. 40 W/m2).

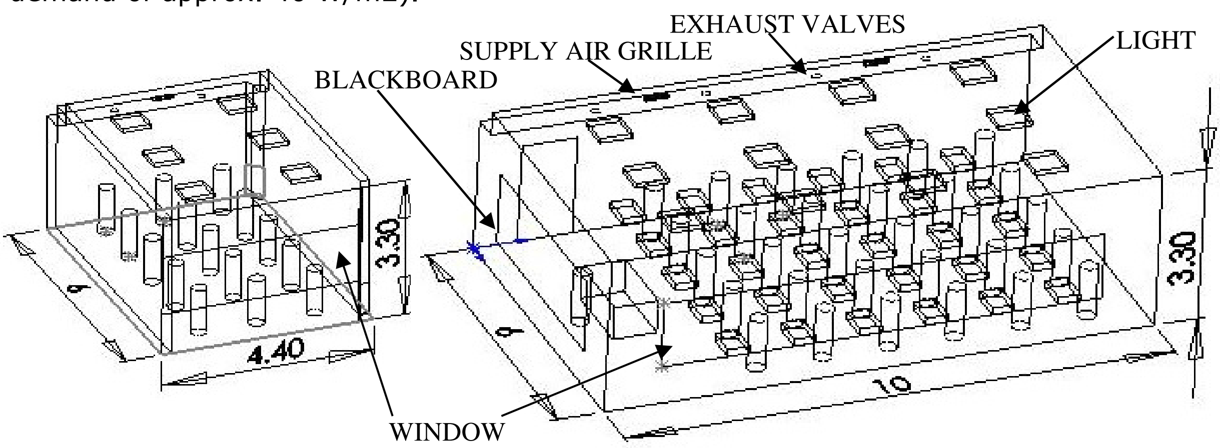


Figure 1. Geometry set up of half classroom in the full-scale laboratory test and in CFD simulation (left) and geometry of simulated whole classroom (right) both in summer cases

Table 1. Heat balance of the simulated whole classroom case (approximately half of the internal heat loads/losses and half of the supply air flow rate used in the half classroom case)

	Summer (room temp. 26°C)	**Winter (room temp. 21°C)**
Occupants	31 x 58 W = 1798 W	16 x 58 W = 928 W
Lights	900 W	900 W
Window	30°C ~ 358 W	11 °C ~ -896 W
Walls	-1000 W	-784 W
Radiators (4 pcs under window)	0 W	500 W (DV 0 W)
Supply air	180l/s at17.0°C (Displ.vent. case 18.6°C)	180 l/s at 18.0°C (Displ.vent. case 20.5°C)

Same cases were simulated with computational fluid dynamics (CFD) software. The measurement details are described in the Table 2 and CFD modelling details in the Table 3. After comparing and ensuring similar measured and simulated flow patterns as well as temperature/velocity levels in the room, the whole classroom was simulated with CFD. The thermal comfort level has been evaluated by comparing velocity, temperature and draft rate distribution. Indoor air quality has been measured by comparing age of air distribution with different air distribution methods.

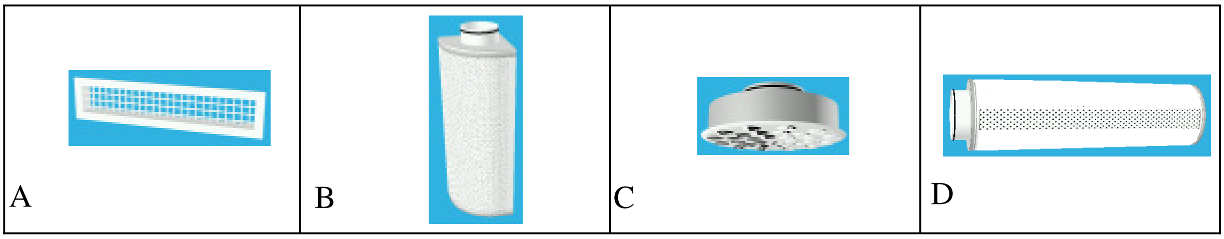


Figure 2. Air distribution in different cases: A) Mixing ventilation with wall grille direction horizontally fan-shaped, B) Displacement ventilation with low velocity units in two corners, C) Mixing ventilation with multi-nozzle ceiling diffuser (in whole classroom case, other ceiling diffuser in half classroom) and D) Mixing ventilation with perforated duct diffuser

Table 2. Full-scale test details

Heat load/loss modelling	Dynamic energy simulations used for defining room temperature and heat loads/losses
	Occupants with metal cylinders according DIN 4715-1 standard with holes on top blocked
	Real lighting units
	Heated/ cooled window surface
	Controlled ambient temperature simulating effect of thermal mass
Measurement devices	Velocity and turbulent intensity with omni-directional hot sphere anemometers HT412 (accuracy +/- 0.02m/s and +/- 1 % of readings with velocities 0.05 - 1.0m/s), 3 minute average readings
	Temperature with PT100 sensors (accuracy +/- 0.1degC)
	24 measurement pole locations and 7 sensor heights: 0.1/0.5/0.9/1.3/1.8/2.4/3.1m from floor
	Black ball temperature measured in one location in the middle of the room
	Air distribution with different schemes was visualized with smoke

Table 3. CFD simulation details

CFD software	Ansys CFX 12.0
Grid resolution	Unstructured grid of 0.5-1.4 million unstructured elements or 120-320 thousand nodes
	Inflation layers used near surfaces and finer grid on the trajectory of supply air jets
Turbulence	SST turbulence model with automatic wall treatment
Buoyancy	Buoyancy is modeled with Boussinesq approximation
Solution	Steady state solutions. Convergence so good as possible (usually some fluctuation due to the interaction of supply air jets and heat plumes). Solved with high resolution numerical scheme with blend factors (2nd order when applicable) except turbulence with first order discretization scheme
Radiation	Radiation modeled with discrete transfer model
Supply air unit CFD model	Momentum method used for CFD model of supply air grille, displacement ventilation unit, ceiling diffuser and perforated duct diffuser, and flow pattern compared to the measurements

RESULTS

Supply air throw pattern, measured/simulated velocities and temperatures were compared in the half classroom test using different air distribution methods. The measured and simulated results of the half classroom were reasonably close to one another. Visualizations of supply air jet flow patterns in the summer are shown in the Fig. 3, below it CFD simulation results for whole schoolroom are presented.

Thermal comfort was compared in the Fig. 4 and 5 by showing draft rate distribution in the whole classroom. Air distribution with supply air grille gave uniform conditions, but they may cause problems due to overly high local velocities. Supply air jet from perforated duct diffuser and ceiling diffuser tended to be carried along thermal plumes from the heat loads.

When comparing the mixing ventilation methods, the air distribution with ceiling diffuser gave the most optimal thermal comfort conditions. Thermal conditions were also very good with displacement ventilation when taking into account the near zone of the low velocity unit.

Average age of air values and air change efficiencies (ASHRAE, 2005) in the occupied zone are listed in table 4. As expected average indoor air quality in the occupied zone was best with displacement ventilation. However there were local areas with poorer air change efficiencies as shown in the Fig. 6 and 7, which should be taken into account in design. In summer conditions there was clearly lower air change efficiency in the area where low velocity units were located and in winter conditions in the area in the other end of room. Average age of air in all mixing ventilation cases was quite uniform and near fully mixed situation.

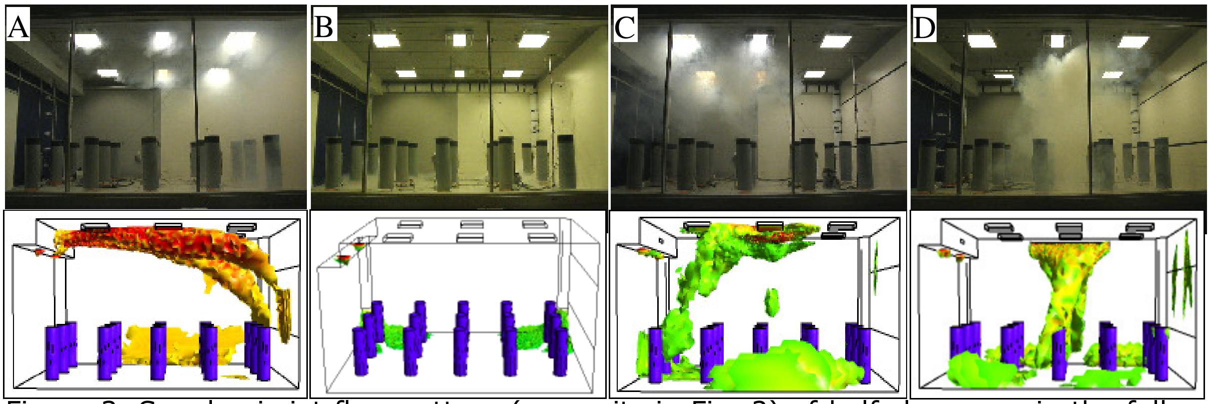


Figure 3. Supply air jet flow pattern (see units in Fig. 2) of half classroom in the full-scale laboratory test in summer conditions (visualized with smoke) and in CFD simulation (velocity iso-volume at over 0.35/0.20/0.25/0.25 m/s)

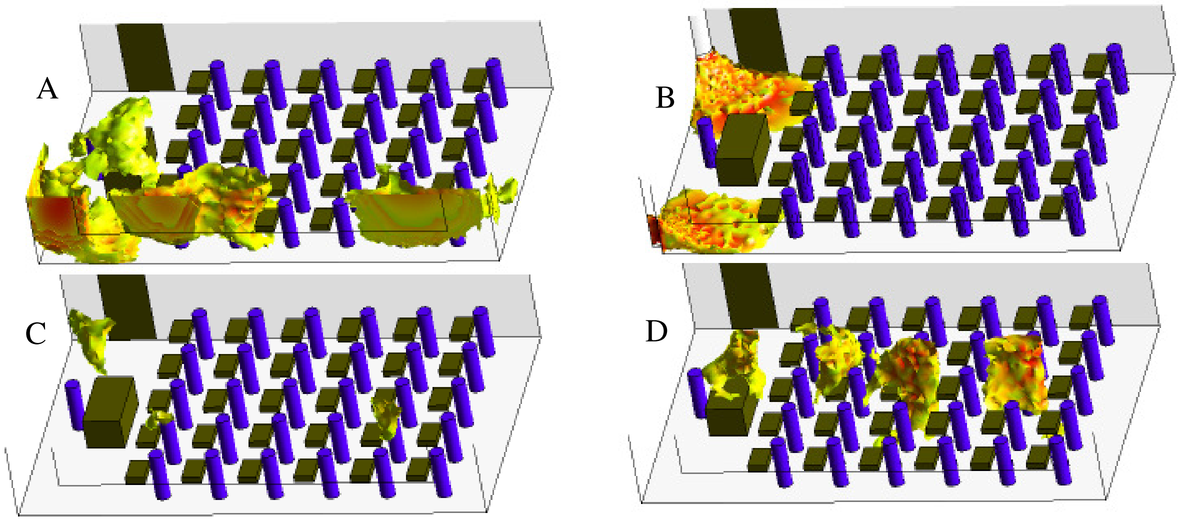
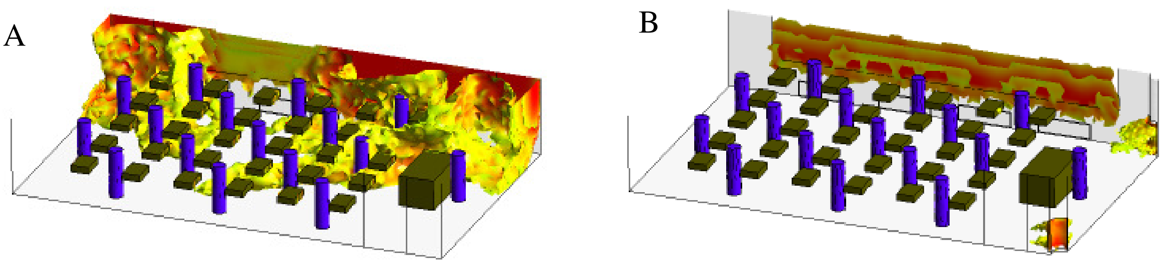


Figure 4. Locations in the occupied zone where draft rate over 15% in whole classroom and in summer conditions



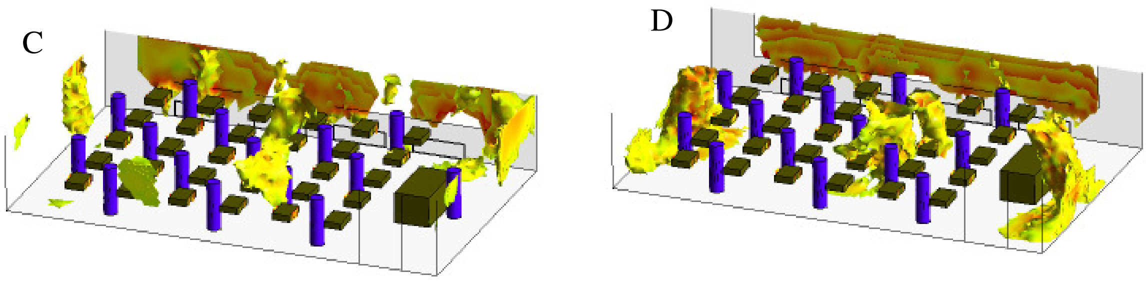


Figure 5. Locations in the occupied zone where draft rate over 15% in whole classroom and in winter conditions

Table 4. Average age of air and air change efficiency in the occupied zone

Average age of air (above) and air change efficiency (below) in the occupied zone	A) Wall grille	B) Displacement ventilation	C) Ceiling diffuser	D) Perforated duct diffuser
Classroom in summer conditions	1005 s	764 s	1029 s	1023 s
	1.06	1.39	1.03	1.04
Classroom in winter conditions	1037 s	907 s	1134 s	1001 s
	1.03	1.17	0.94	1.06

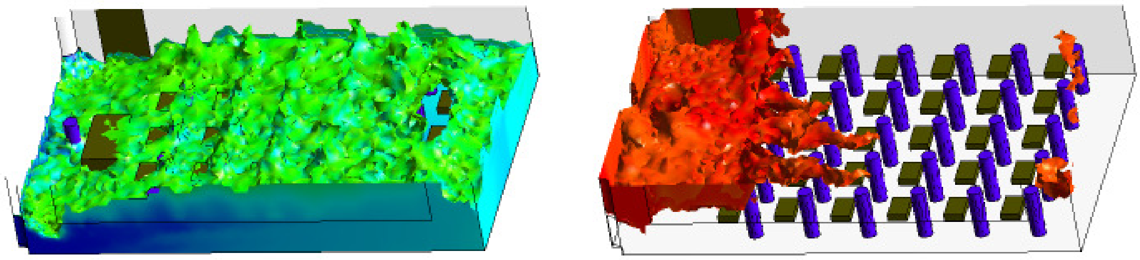


Figure 6. Locations in the occupied zone where age of air over 25% younger than fully mixed situation on the left and over 25% older than fully mixed on the right in summer conditions

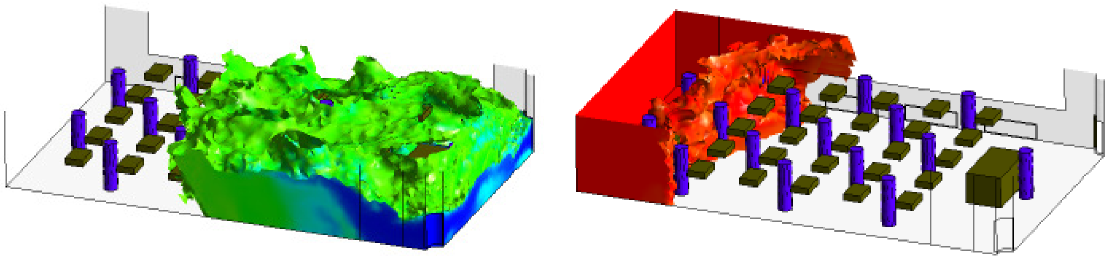


Figure 7. Locations in the occupied zone where age of air over 25% younger than fully mixed situation on the left and over 25% older than fully mixed on the right in winter conditions

DISCUSSION

Internal heat loads can have a significant effect to the air distribution, and therefore to the indoor climate. In this paper the effect has been evaluated with different air distribution arrangements, which provides essential information when designing effective classroom ventilation. The analysis of the indoor climate was based on CFD simulations of the whole classroom and to the age of air calculation. In order to ensure the quality of the CFD simulations, they were first done for a half classroom and then compared with the identical full-scale test in controlled measurement chamber. Due to the interaction of thermal plumes and supply air jets, the solution was fluctuating a bit in the mixing ventilation tests.

This would effect to the draft rate and age of air distribution or locations somewhat, but it would not change their levels in the occupied zone. The displacement ventilation test proved more stable.

It was found that the indoor climate in the occupied zone was best with displacement ventilation. Still there are some design aspects that should be taken into account. In the summer conditions with units located at teacher's end of the classroom, supply air was distributed well to the other end, but it rose before it reached teacher's end again, which leads to poorer local air change effectiveness. This was caused by the location of most of the heat loads at other end of the room, which caused the fresh air to rise up, and by the location of the exhaust valves. Also in winter conditions, the nearly isothermal supply air tended to rise before it reaching other end of the room. If cooler supply air is used, the air temperature in the occupied zone would too low. A good solution for these issues would be to use a low velocity unit in every corner of room. Another solution would be locate two units to the both corners of the long wall with door. Only issue in that case is to take into account the effect of near zone of the low velocity unit located close to students. The CFD simulation with Reynolds-averaged turbulence models can give a bit over-estimated picture of this situation, but still this aspect should be taken into account.

CONCLUSIONS

This paper presented a comparison of the indoor climate in the modelled classroom with most used mechanical air distribution systems. The air distribution with displacement ventilation and radial ceiling diffuser gave the most optimal indoor climate conditions. Wall grilles for supply air distribution gave uniform conditions, but they may cause problems due to too high local velocities. Air change effectiveness in the occupied zone was the most efficient with displacement ventilation. Still locations of the low velocity units should be considered carefully for getting uniform conditions into the occupied zone.

ACKNOWLEDGEMENT

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