Temperature distribution and ventilation in large industrial halls

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Abstract
In this study vertical temperature gradient was measured and ventilation need was analyzed in two hall buildings with room height close to 10 m. One building was industrial assembly hall (without process) and another heated and ventilated warehouse. Both buildings had high ventilation rate of about 2 l/(s m²) and well insulated building fabric according to the Finnish building code values. One objective was to measure differences in the temperature distribution as one building had air heating and another one radiant ceiling panel heating. This was quantified by vertical temperature gradient measurements in winter. Another objective was to assess minimum ventilation need in such halls. For that purpose available literature on indoor sources and ventilation needs was reviewed. The results showed about 0.2 K/m vertical temperature gradients in both halls which is by factor 5 smaller for air heating than the guidebook value likely because of ventilated and well insulated building. Temperature gradients kept reasonably constant at all measured outdoor temperatures. The differences caused by air heating and ceiling panel heating were very small, however, in the case of air heating, room temperature control was less accurate and the setpoint was not always achieved. Ventilation need analyses showed that studied buildings were over ventilated by about factor 2 and 1 l/(s m²) would be relevant design value for general ventilation in such halls with low occupancy and low polluting materials.

Keywords: Temperature gradient, stratification, industrial halls, ventilation need

1 Introduction
Modern industrial halls are often assembly halls without significant process generating neither pollutants nor heat gains. Such buildings in Finland are well insulated, heated and ventilated that applies also for many warehouses. In a cold climate, heating dominates in energy use and space heating solutions combined or not combined with ventilation may have significant effect on energy performance. For air heating and ceiling panel heating, studied in this paper, handbooks provide quite different vertical temperature gradient values due to stratification, 1.0 K/m vs. 0.2 K/m respectively (Kabele 2011). This indicates that ceiling panel heating can save energy not only because of avoiding some fan energy but also due to lower heat losses from upper part of a building. However, it is not known how valid an old handbook values are in well insulated halls with mechanical supply and extract air ventilation which is mixing indoor air and could reduce stratification.

Another debated issue in halls is evidence based ventilation need. In Finland a default code value of 2 l/s per floor m² (D2:2012) has been widely used, but in practice it is often noticed that the occupancy is low and halls are over ventilated which is indicated by extremely low CO₂ concentrations.
The objective of this study was to quantify energy saving potential of ceiling panel heating due to smaller vertical temperature gradient relative to air heating system. For that purpose vertical temperature stratification was measured in two modern halls with described heating systems. Measured temperature gradient results could be applied in energy simulations which are possible to run with actual ventilation rates and with lower ventilation rates suggested by scientific literature. In this study we were however limited on thermal comfort and ventilation aspects, i.e. on temperature gradient and general ventilation need, parametric energy simulations based on these results are planned to be conducted in future study.

2 Methods
Measurements were conducted in Assembly hall with air heating in Hämeenlinna, construction year 2006, and in Warehouse with ceiling panel heating in Vantaa, construction year 2008. Both buildings are heated, ventilated and well insulated hall buildings, Figure 1. Heating and ventilation solutions are shown in Figure 2. Regarding thermal insulation and ventilation both of these halls follow Finnish building code U-value reference values (C3:2003) and ventilation recommendations (D2:2003):

- External walls U = 0.25 W/(m² K)
- Roof U = 0.16 W/(m² K)
- Slab on the ground U = 0.25 W/(m² K)
- Ventilation rate 2 l/(s m²)
- Building leakage rate at 50 Pa 4.0 1/h (measured value at the assembly hall 0.9 1/h)

Figure 1 Photo of Assembly hall with air heating in Hämeenlinna, construction year 2006 (left) and Warehouse in with ceiling panel heating in Vantaa, construction year 2008 (right).

Figure 2 Ventilation and air heating in Assembly hall (left), temperature measurement from ceiling and supply air duct can be seen. Warehouse with ceiling panel heating and similar ventilation (right).
In the measurements the pressure difference from outdoor to indoor air was measured by KIMO CP101 pressure transmitter. The measuring range of pressure transmitter was -500 to +1000 Pa with 1Pa resolution and output was displayed in 0-10V or 4-20mA. After that, indoor air temperature was measured by Pt100 temperature sensor. It could measure temperature in between -40°C to +60°C with resolution of 0.1°C and temperature output range was 0-10V. 23 sensors were calibrated in laboratory during 1 hour and 12 sensors were selected which gave similar data. USB temperature loggers were used to measure the outdoor temperature. The measuring range was -40°C to +70°C with resolution of 0.1°C. The USB data loggers also well calibrated in laboratory before onsite measurement.

In this study, KIMO CP101 pressure transmitter integrated with data logger and pressure differences were recorded with 10 second interval in Warehouse and Assembly hall. Temperature sensors in Assembly hall were placed along height with distance of 0.10, 1.86, 3.86, 5.86, 7.06 (supply air point) and 8.66m respectively from floor surface, Figure 3, and measurements were taken from 10.12.2014 to 22.02.2015. In warehouse temperature sensors were placed with distance of .10, 1.86, 4.11, 6.11, 9.13 (supply air point) and 9.83m respectively from floor surface and measurement period was 19.12.2014 to 11.3.2015. Those Pt100 sensors were connected with data logger which recorded temperature in 10 minutes interval. Measurement period of outdoor temperature followed the same measurement duration for both buildings. Two USB temperature data loggers were placed in northern and southern direction in both sites and recoded in 10 minutes interval.

![Figure 3 Location of temperature sensors in Assembly hall with air heating system (left) and in Warehouse with ceiling panel heating (right).](image)

### 3 Results and discussion

#### 3.1 Ventilation need in assembly halls, retail buildings and warehouses

Ventilation need was assessed based on existing standards, scientific literature and building code values. Most of scientific literature was found for retail buildings which are also adequately described in EN 15251:2007 and ASHRAE 62.1-2013 standards as well as in Finnish building code part D2:2012. Industrial halls (neither assembly halls nor warehouses) are not specifically mentioned in EN 15251, but the occupancy and building material emission based method may be applied for them for general ventilation need assessment if specific pollutants are not handled or produced by processes in such halls. In addition to general ventilation, evidently source control (local exhausts) are needed to control polluting processes.
EN 15251 method calculates the total ventilation rate for the breathing zone by combining the ventilation for people and building:

\[ q_{\text{tot}} = n \cdot q_p + A_R \cdot q_B \]  

(1)

where

- \( q_{\text{tot}} \) = total ventilation rate for the breathing zone, l/s
- \( n \) = design value for the number of the persons in the room,
- \( q_p \) = ventilation rate for occupancy per person, l/(s* person)
- \( A_R \) = floor area, m²
- \( q_B \) = ventilation rate for emissions from building, l/(s, m²)

With EN 15251 indoor climate category II and low polluting material values in the case of one person per 25 m² floor area in industrial halls it results in (1 pers*7 l/(s pers) + 25 m²* 0.7 l/(s m²))/25 m² = 0.98 l/(s m²). In supermarkets and shopping malls the reported occupancy densities are higher. Karjalainen (2015) ended up with 20 m² per person in a weekend rush hour (duration about 6 hours) and for weekday rush hour about 30 m² per person (duration 3 hours) in Finnish supermarkets. Stensson (2014) measured occupancy in 11 Swedish shopping malls where maximum occupant densities were 40 m² and 14 m² per occupant during weekdays and weekends respectively, however in most of shopping malls occupant densities were much lower. 14 m² per occupant results in 1.2 l/(s m²) ventilation rate with EN 15251 equation (with category II and low polluting values) which is the same ventilation rate ASHRAE 62.1-2013 prescribes assuming 11 m² per person occupant density.

California’s building energy efficiency standards (Title-24) require retail stores to provide adequate ventilation to satisfy both 7 l/s per person and 1.0 l/(s m²), where the per floor area value is often used for design purposes. At default occupant density, these minimum ventilation rates are similar to the specifications in ASHRAE 62.1-2013. Finnish building code has no minimum ventilation rate requirements but provides recommended default values which may be used in order to comply with general healthy and comfortable ventilation requirement. For industrial halls and retail buildings 2 l/(s m²) and for warehouses 0.5 l/(s m²) are recommended. There is no scientific references behind these values, however the high occupant density provides some justification for retail buildings. A common design practice of all air (air heating and cooling with ventilation system) supports higher airflow rates.

Chan et al. (2014) measured ventilation rates and pollutants concentrations in 21 retail stores in California. One naturally ventilated store was clearly below the requirement of 1 l/(s m²) being 0.4 l/(s m²), two stores were close to the requirement (0.8 and 0.9 l/(s m²)), 10 in between 1 and 2 l/(s m²) and 8 had higher ventilation rate than 2 l/(s m²). Formaldehyde concentrations measured in furniture/hardware stores tended to be higher than in the other two store types and often exceeded California’s OEHHA guideline (2014) of 9 µg/m³. Merchandise containing composite wood products was likely a key indoor source of formaldehyde in furniture/hardware stores. The source strengths of acetaldehyde in grocery stores, likely from baking, were much higher than in the other stores. Besides formaldehyde and acetaldehyde, few VOCs with established health guidelines had measured concentrations that were near the levels of concern. The source strength analysis from this study indicated that even if stores were to ventilate at twice the minimum
ventilation requirement, formaldehyde concentrations in retail stores would still exceed California health guideline. Therefore, to maintain the formaldehyde levels in retail stores below the guideline value the study concluded that source control instead of increasing ventilation rate is a viable strategy.

In another study Chan et al (2015) measured in grocery stores having adequate ventilation according to ASHRAE 62.1-2013 significantly higher concentrations of acrolein, fine and ultrafine PM, compared to other retail stores, likely attributable to cooking. To lower acrolein concentration a substantial increase in outdoor air ventilation rate by a factor of three from current level would be needed. Alternatively, it was recommended to reduce acrolein emission to indoors by 70% by better capturing of cooking exhaust.

Dutton et al. (2015) measured ventilation rates and concentrations of of volatile organic compounds (VOCs) in 13 stores. Mass balance models were used to estimate ventilation rate that would maintain concentrations of all VOCs below health- or odor-based reference concentration limits. These ventilation rates ranged in between 1 and 10 ach in 11 stores and were even higher in two last stores indicating the importance of the source control.

Ng et al. (2015) modeled in big box retail buildings two ventilation strategies: (1) 1.2 l/(s m²) of outdoor air during occupied hours, which is the ventilation rate prescribed in ASHRAE 62.1-2013 for retail buildings assuming approximately 9 occupants per 100 m², and (2) 0.4 l/(s m²) 24 h a day based on the IAQP analysis performed by Bridges et al. (2013). In Bridges et al. (2013), the concentration of formaldehyde, selected VOCs, and carbon monoxide (CO) were measured over 48-h periods in retail buildings. The 0.4 l/(s m²) ventilation rate was based on the minimum calculated ventilation rate required to maintain formaldehyde below 100 µg/m³, TVOC below 1000 µg/m³, and CO below 10 mg/m³ assuming steady state conditions. This study demonstrated that ventilating at a lower rate (0.4 l/(s m²)) for 24 h a day saved energy compared with ventilating at the higher rate (1.2 l/(s m²)) and that the simulated indoor contaminant concentrations did not exceed common benchmarks or health guidelines, however the higher rate led to somewhat lower concentrations.

The importance of adequate ventilation was shown in the survey by Zhao et al. (2015). This study including 611 employees in 14 retail stores concluded that the air exchange rate is the most influential parameter on the employee perception of the overall environmental quality and self-reported health outcome. Measured air change rates were in between 0.2 – 1.5 1/h and it was found that when the air change rates increased from 0.6 ach to 1.2 1/h, the probability of common cold infection frequency decreased by 43%. It should be noted that in the case of 4 m room height 1.2 1/h corresponds to 1.3 l/(s m²).

Available evidence in these studies shows that general ventilation only cannot remove pollutants in all cases such as merchandise containing composite wood products or poor capturing of cooking exhaust. If source control (i.e. local exhausts) will be applied for such cases the values in EN 15251 and ASHRAE 62.1 standards, i.e. about 1.0 l/(s m²) for industrial halls with lower occupancy and about 1.2 l/(s m²) for retail stores with high occupancy are likely to be reasonable approach for general ventilation. In the case of all air systems (heating and cooling via ventilation), required air flow rates are to be checked based on heating and cooling needs and if necessary air flows may be boosted by recirculation.

3.2 Vertical temperature gradient measurement results
In this section the temperature gradient measurement results over a 3 month period are reported in Warehouse with ceiling panel heating and Assembly hall with air heating system.
The operational strategy of both systems was not similar during office and non-office hour. Results are presented for Office Hour (OH) and Non Office Hour (NOH) so that OH were considered from 8-18 hours during weekdays and rest of hours in a week were considered as NOH. Heat was distributed in Assembly hall by ceiling supply air valves and supply air temperature was found in between of 18.5 to 20.5°C which compensated with outdoor air temperature. In Warehouse heating was provided by ceiling panels and partly also by supply air valves. The supply temperature from ceiling valves was in between of 18.0 to 19.5°C based on outdoor temperature. Air temperature at different height from floor level during OH is shown in Figure 4.

Figure 4 shows the indoor temperature behavior along height at different outdoor temperatures. Outdoor air temperature has stronger impact on indoor air temperature in air heating system compared to ceiling panel heating. The average temperature at point P1 and P2 were 18.9 and 17.6 °C for Assembly hall and Warehouse respectively during measured OH period (see locations from Figure 3). In NOH supply air temperature was decreased in Assembly hall and in Warehouse the ventilation was switched off. The results from NOH are shown in Figure 5.
During NOH the average temperature at point P1 and P2 in Assembly hall and Warehouse were recorded of 17.9 and 17.3°C respectively. With lower supply air temperature indoor temperature dropped in Assembly hall. The supply air temperature difference during OH and NOH is shown in Figure 6 where indoor temperature is calculated as an average value of P1 and P2 measurement points. In the case of NOH in Warehouse, supply air temperature (ventilation switched off) corresponds to indoor temperature at supply air valve height.

Figure 6 illustrates air heating performance in Assembly hall, however at low outdoor temperatures there seems to be a lack of supply air heating capacity. Results are unexpected in Warehouse where ceiling panel heating is a main heating source, but supply air is also heated. Ceiling heating has likely been an additional installation and supply temperature curve has not been corrected afterwards to a constant setpoint which could be expected as a common operation mode for ceiling heating.

Heating source location had an effect on temperature gradient along building height. In Assembly hall supply air valve was located 7.06 m from ground floor and visible difference of gradient was observed from measured points P1-P4 and P4-P6. In Warehouse ceiling panel was the primary source of heating and the supply air at 9.13m from ground floor had smaller effect on temperature gradient. Temperature gradient from ground floor to below supply air valve (P1-P4 point) and over supply air valve to ceiling (P4-P6 point) is shown in Figure 7.
The negative temperature gradient in Assembly hall indicated that nearby ceiling air temperature was colder compared to the supply air temperature for air heating system. The temperature gradient from point P1-P4 was steady compared to point P4-P6 in Assembly hall. In Warehouse, temperature gradient was quite steady and outdoor temperature had less effect on it. The weighted average temperature gradient during OH were 0.09 and 0.2 K/m for Assembly hall with air heating system and Warehouse with ceiling panel heating respectively. During NOH the scenario of temperature gradient had changed because of lower supply air temperature/switched off ventilation, Figure 8.

During NOH the supply air temperature was low compared to OH and its effect was clearly visible at weighted average and average temperature gradient in Assembly hall. In Warehouse almost similar results were found during OH and NOH. In addition, outdoor temperature had less significant effect on temperature gradient compared to Assembly hall. The difference of weighted average temperature gradient during OH and NOH was 0.1 K/m in Assembly hall whereas in Warehouse it was very small i.e. 0.01 K/m.

4 Conclusions
This study conducted vertical temperature gradient measurements and ventilation need review on thermal comfort, general ventilation and energy assessment purposes in large hall buildings. The results serve as an input data for energy analyses which will be conducted in future study.

Ventilation need review indicates that ventilation in Finnish industrial hall buildings is commonly oversized by about factor 2 based on the default values of the Finnish building code. Available evidence suggests that about 1.0 l/(s m²) general ventilation is needed in industrial halls with lower occupancy and about 1.2 l/(s m²) in retail stores with high occupancy up to 11 m² per person occupant density. There is reported evidence that general ventilation only cannot remove pollutants in all cases such as merchandise containing composite wood products or poor capturing of cooking exhaust. In such cases source control (local exhausts) is needed to remove effectively pollutants and this has been more effective measure than increasing general ventilation rate.

Measured results showed about 0.2 K/m vertical temperature gradients in both halls which was expected result for the ceiling panel heating, but by factor 5 smaller for air heating than the guidebook value. Ventilation with high airflow rate, well insulated building and significant
lighting power during operating hours are possible reasons explaining very small temperature gradient in the air heating case. Temperature gradients kept reasonably constant at all measured outdoor temperatures and there was no difference between air heating and ceiling panel heating. The only difference observed was the higher fluctuation of room temperature in the case of air heating indicating some limitations in the temperature control of air heating.

References