Simulation of Ventilation Rates and Heat Losses during Airing in Large Single Zone Buildings in Cold Climates

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Abstract. Airing can be a solution to introduce extra ventilation in large single zone buildings, especially where there are large aggregations of people such as churches or atriums. In naturally ventilated domestic and ancient buildings, opening of a window or door can introduce extra fresh air and remove particles and other contaminants emitted from people and other sources such as lit candles in churches. However, the energy use might be an issue in cold climates, where airing might lead to waste of heated air, at the same time as indoor air temperatures can be uncomfortably low. In the present study, the energy loss and ventilation rate due to airing in a large single zone (church) building is investigated via IDA-ICE simulation on annual basis in cold weather conditions. The results can be used in order to prepare airing guidelines for large single zone buildings such as atriums, churches, industry halls and large sport halls. According to the results, one-hour of airing in the studied church building resulted in 40-50 % of exchanged room air and, if practiced once a week, an increase of around 1 % in heating energy.

Keywords: Airing (single-sided ventilation), IDA-ICE simulation, Large single zones.

1 Introduction

Natural ventilation is the outdoor flow penetrating into a building through purpose provided openings on the building envelope. There are different types of natural ventilation including single-sided, cross and stack ventilation [1]. Single-sided or cross ventilation are also called airing which is intentional air exchange through large openings such as windows and doors [2]. That is, when the opening(s) are located on the same façade, i.e. single-sided ventilation, or on different facades, i.e. cross flow. Airing can be used for refreshing the interior air and extracting the pollutants especially after aggregations or occasions when there are many people and – in case of churches – lit candles. Airing can be used alone in naturally ventilated buildings or even as a complement for mechanical ventilation at schools, for example see [3], especially in occasions when there are many people present at the same time and the high amount of CO_2 should be diluted.

Airing is a complicated phenomenon. There are different parameters that affect the airing flow rates, such as the terrain surrounding a building, the position of the opening on a building envelope as well as opening size (height, width and depth), building air tightness, distribution of the leakage on the envelope, weather conditions including wind speed and direction and its turbulence. There are other factors, which might limit the applicability of the airing occasions such as ingress of noise and pollutants.

Driving forces for airing are buoyancy and wind effect in a naturally ventilated building. The temperature difference between inside and outside induces a pressure difference across the opening. However, wind effect is more complicated; and not only the average wind velocity but also turbulences in the wind affect and induce airflows [2]. Wind direction is a deciding parameter. Previously performed tracer gas measurements showed that the single-sided windward flows can be up to more than two times larger than the leeward flow, i.e. when the porch is located in the leeward side [4].

Hayati [2] also investigated the airing flow rate via model studies in a wind tunnel and found higher air flows when the porch is located in the windward side in comparison to the cases when the porch is located in the leeward side. Different models have been developed for combining these effects and make a prediction of the total air flow through openings, see for example [5–7]. A summary of the airing models for single-sided ventilation through large vertical openings is presented by Hayati et al. [4].

Airing and the models for airflow through large vertical openings is validated by Hayati, et al. [8-9], especially the reliability of the models used in IDA Indoor Climate and Energy (IDA-ICE) for predicting the single-sided flows in large single zone buildings. IDA-ICE is software for simulation of energy use and indoor climate for individual zones as well as the whole building. IDA-ICE involves dynamic simulation of a single or multi-zone building with a system of boilers, chillers and air handling unit(s). Room units (heaters/coolers) and local air handling units are also available. Neutral Model Format (NMF) is used as the coding language for implementing the mathematical models in the program. The building model can be supplied with synthetic or actual weather file. An actual weather file in IDA-ICE consists of time (hour), air temperature (°C), relative humidity (%), wind speed (m/s) and direction, direct normal beam radiation (W/m^2) and diffuse radiation on horizontal surface (W/m^2). The models simulate air containing both CO_2 and humidity. In IDA-ICE, airing flow is calculated based on the Bernoulli equation (the so-called orifice flow equation) by assessing the wind pressure difference at the top and bottom of the opening. The program takes into account both buoyancy and wind (caused by averaged wind speed) effects [9]. Air leakage is modelled by means of power law equations [10].

Ancient buildings like churches are naturally ventilated via leakage, i.e. air infiltration or via openings such as windows or doors. Normally there are also limited possibilities to add some mechanical ventilation or tightening the envelope in such buildings because of esthetical and preservation aspects. Other concerns include air humidity and particle deposition, which might deteriorate different pieces of art inside. Napp and Kalamees [11] studied the possibilities of implementing different climate control systems in churches by performing IDA-ICE simulations, addressing above mentioned restrictions.

The energy loss due to airing in cold climate is investigated in different studies with the aim of introducing a national standard value to be used in residential building energy simulations [12]. Different suggestions in order to compensate the airing effect on energy use include the addition of 4 kWh/(m^2·year) to the yearly specific energy use (for residential buildings) or adding the equivalent airing flow to the air infiltration rate or mechanical ventilation rates [13–16]. Among the suggested compensating methods, addition of energy is recommended because airing is a temporary measure in order to increase the flow rate and refresh the interior occasionally when it is needed. In office buildings, there is no default value suggested since airing is considered to be negligible [17]. However, air flow through entrance or garage doors through which many persons are passing may be significant but due to the lack of previous studies, no standard value can be put forth.

The aim of this study is to investigate the effect of airing on energy use in naturally ventilated single-zone church which is located in cold climates. By means of simulations with IDA-ICE, a validated model of the church is used to predict increase in specific energy use due to one hour of airing after Sunday mass (every week per year). This also involves assessment of air exchange in the zone during the airing occasions.

2 Method

The original model was from a church located in Hamrånge, mid Sweden [9]. The same model was simulated, using weather data from Kiruna, in the north of Sweden and Gothenburg (Göteborg), located in the south-west of Sweden. The church constitutes a great hall with thick stonewalls, has rendering on both inside and outside, and with double outer doors to enter the large hall. It is equipped with gable roofs and inner ceilings that are plastered on the inside and well insulated on the outside with wind barrier- coated mineral wool towards a naturally ventilated attic. Windows are double-glazed and weather-stripped. The church has a crawl space underneath a wooden floor, consisting of double boards with a ~15 cm layer of lime sand in between. The church is naturally ventilated through leakages in the building envelope. Size characteristics are summarized in Table 1. The interior zone of the church is not perfectly cuboid since ceilings are vaulted and resemble more or less semi-cylindrical or semi-spherical shapes. Thus, the ceiling height is not a fixed value. However, the simulated model includes simplifications of the actual church regarding the interior shape.

Table 1. Size characteristics of church.

Volume (m^3)	Floor area (m^2)	Ceiling area (m^2)	Wall area (m^2)	Max ceiling height (m)	Average ceil-ing height (m)
7620	695	862	1188	13.7	11.0

The church model was validated against measurements in Hamrånge regarding both the indoor temperatures and the airing flow rates [9]. The weather data for Hamrånge, used in this study, was obtained from Swedish Meteorological and Hydrological Institute (SMHI) available at [18]. The weather data used in the current study for Kiruna and Gothenburg were obtained from the ASHRAE IWEC 2 database, which contains "typical" weather files for 3012 locations available for direct downloading via the IDA-ICE program. The files are also derived from Integrated Surface Hourly (ISH) weather data originally archived at the National Climatic Data Center [10].

Air flow through large vertical openings like doors has been investigated in previous studies [8-9] and the simulation results were compared with the airing rates, measured by tracer gas decay method in the interior, the main hall of the church. The studies [8-9] showed that the simulated single-sided flows were in the same order of magnitude of the measured ones, although slight over-prediction was observed when the porch was in the windward as well as slight under-prediction when the porch was on the leeward side. However, larger over-prediction was observed in case of cross flows. But overall, it seems that IDA-ICE simulation regarding single-sided airing flow is adequate enough to be used in this study for other climates, i.e. the cold climate of Kiruna and windy Gothenburg, in order to investigate the energy loss and the ventilation flow rates during the airing period.

The church was modeled and simulated in IDA-ICE simulation program version 4.7.1. There, the building was divided into six different zones, including main hall, crawl space, main entrance and the tower, sacristy, attic room and the storage room as shown in Fig. 1. The thick external walls consist of 0.85 m stone with an assumed U-value of 0.4 W/(m^2·K) and default values were used for roof, floor and inner walls in IDA-ICE. Each window is 2.6 m times 4.7 m large and has a U-value of 1.9 W/(m^2·K), solar heat gain value of 0.68 and solar transmittance value of 0.6. The side porches are 1.9 m tall and 2.9 m wide. The building is quite wind exposed. The default values of pressure coefficient (varying with wind direction) for wind exposed building in the program were used in this study; the data are available directly in the program and are originally obtained from handbook data set of the Air Infiltration and Ventilation Centre [19,20].

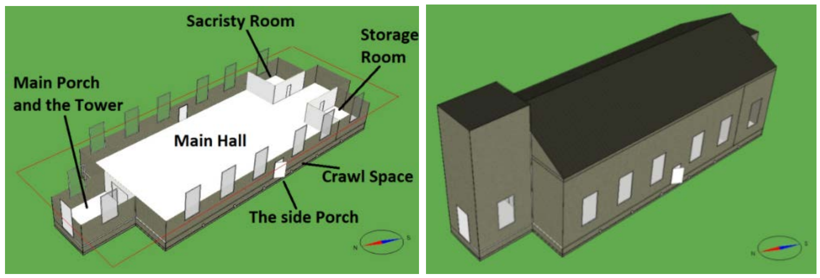

Fig. 1. Hamrånge church model in IDA-ICE.

The occupancy schedule for the main hall was set as 20 people present on Sundays from 10:00 to 15:00 and 2 people present during the rest of the days from 8:00 to 16:00 with half an hour lunch break. The side porch of the church (located on the western façade) was opened one hour directly after each aggregation on Sundays (from 15:00 to 16:00) throughout the whole year. The activity level was assumed as 1 MET for all occupants. No occupancy was assumed for the rest of the zones. The only room units were in the main hall, consisting of 20 electrical bench heaters with 120 kW total power. The heaters were coupled with thermostats working between 15 and 16 °C. Total lighting of 2 kW and 1 kW equipment power was set for the main hall with the same schedule for the occupants. For the storage room and sacristy, 0.5 kW electric heaters as well as 0.2 kW lighting was assumed.

From blower door tests, the permeability of the building envelope was obtained as 3.64 l/(s·m²) at 50 Pa pressure difference (corresponding to 3.42 ACH) and the flow exponent was obtained as 0.86. In IDA-ICE, there is the possibility of entering permeability in form of evenly distributed air leakages. However, the choice was to model air leakage as unevenly distributed effective leakage areas in the facades based on field observations including IR-thermography and analytical model studies so that almost 50 % of the leakage occurs through the floor, 25 % through the surrounding walls of the main hall and 25 % through the ceiling [21]. Thus the total effective leakage area, approximately 0.32 m^2 at 4 Pa (according to [22]) based on blower door test results, was distributed to the different parts at these percentages, see [9].

3 Results and discussion

The results from IDA-ICE simulation are presented and discussed here. As the heating system inside the church is controlled by thermostat and ideal heaters are used in the simulation, the inside temperatures are between 15 and 16 °C, as expected; and this is in line with measured indoor temperatures during airing periods [9]. The ideal heaters in IDA-ICE deliver the given heating capacity to the zone independent of the type of the actual room unit (radiator, convector or etc.); physically, an ideal heater can be considered as a standalone electric heater. Therefore, the focus of the results is on the airflow rates and the percentage of the exchanged room air during the airing period as well as the energy loss due the same airing periods.

The annually averaged air inflow and outflow from the main hall are depicted in Figures 2 and 3. The diagrams include airflow both through the leakage in the rest of the building envelope and through the open porch. The air in- and exfiltration depicted in Figures 2 and 3 is the air leakage during the airing periods, i.e. when the porch was opened. The airing model used in IDA-ICE was validated in previous studies [8-9] which shows that the simulated single-sided air flow rates are of similar magnitude to the measurement data, however the effect of wind direction is less clear in the simulations, maybe due to ignorance of wind turbulence. However, the simulations are run throughout the year and include both windward and leeward cases, and at least regarding the total flow rate and energy loss, the simulated single-sided airing flow rates are judged to be fairly reliable. The difference in the air in- and outflow in Figures 2 and 3 is due to the difference in the air density between the fresh colder air entering the main hall and the warmer interior air exiting the hall. Noticing Figure 3, the reason for the high exfiltration in Gothenburg can be due to the dominating western winds (blowing from the sea on the west side of city) that increase the airing through the westward porch, which in turn pushes the air via the leakages in the rest of the building, i.e. air exfiltration.

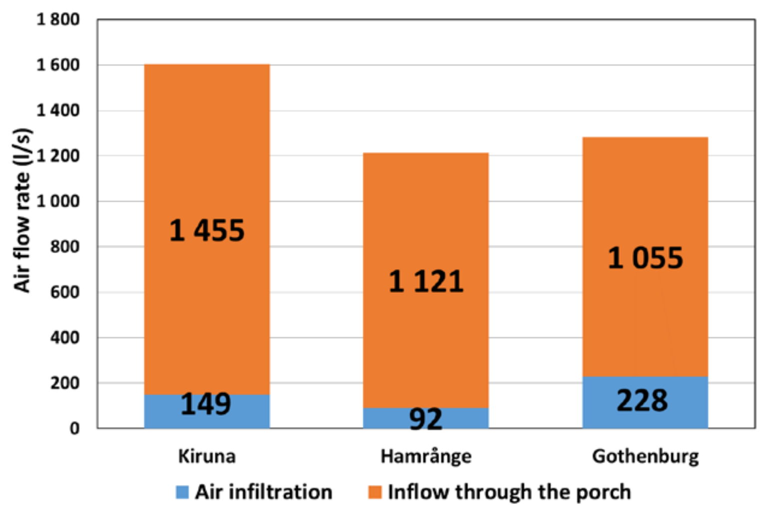

Fig. 2. Air inflow to the main hall, averaged over the whole year due to 1-h airing on each Sunday.

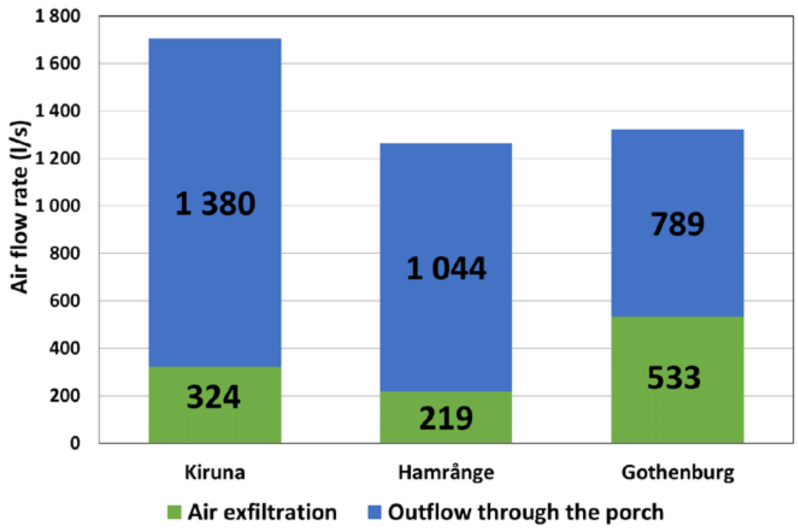

Fig. 3. Air outflow from the main hall, averaged over the whole year due to 1-h airing on each Sunday.

The climate data (including the wind speed and the outdoor temperature) as well as the exchanged room air during porch airing are also depicted for each location (averaged over each month), see Figures 4 and 5. The exchanged room air shown in Figure 5 is the total inflow through both the porch and the leakage in the building envelope.

Noticing Figures 2 and 3, higher flow rates are observed in Kiruna; the colder climate of Kiruna (see Figure 4) which increases buoyancy forces, is the likely reason for larger airing values. The outside temperature is slightly lower for the Hamrånge case in comparison to the Gothenburg climate, and despite of having higher wind speeds in the coastal city of Gothenburg, both cities have almost the same airing flows, see Figures 2 and 3. This can be due to that the wind driven flows are connected with the wind pressure coefficients in IDA-ICE, which in turn depend on the wind direction. As only wind speed is illustrated in Figure 4, further studies are recommended in order to include the wind directions as well other cities/climates in order to analyze the energy loss and the amount of airing flows. Moreover, surveying the airing habits in churches is also recommended in order to map the energy loss due to airing. What is evident from this study is that buoyancy forces seem to influence air exchange to a larger degree than what wind driven forces do.

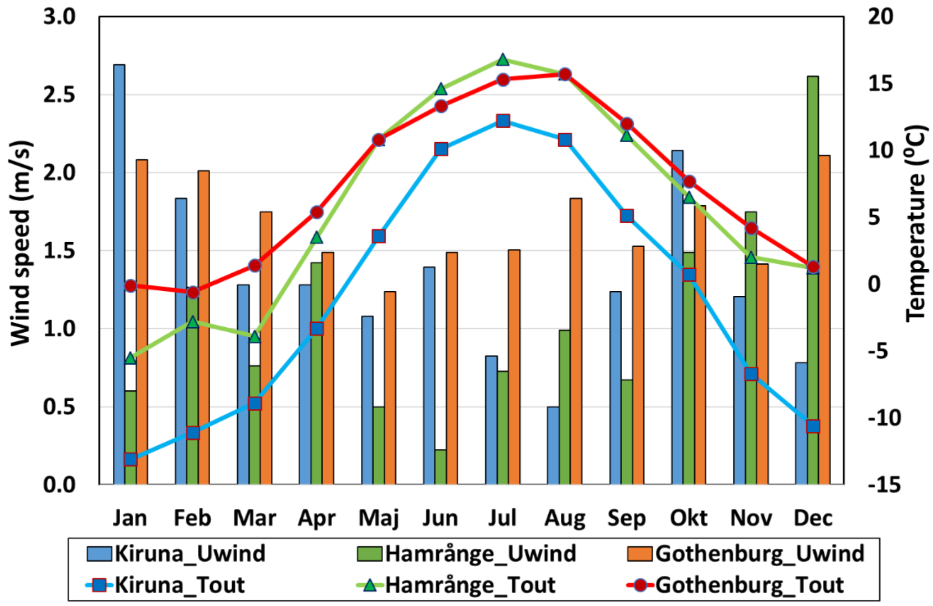

Fig. 4. Monthly averaged weather data including wind speed (Uwind) and outdoor temperature (Tout) for Kiruna, Hamrånge and Gothenburg.

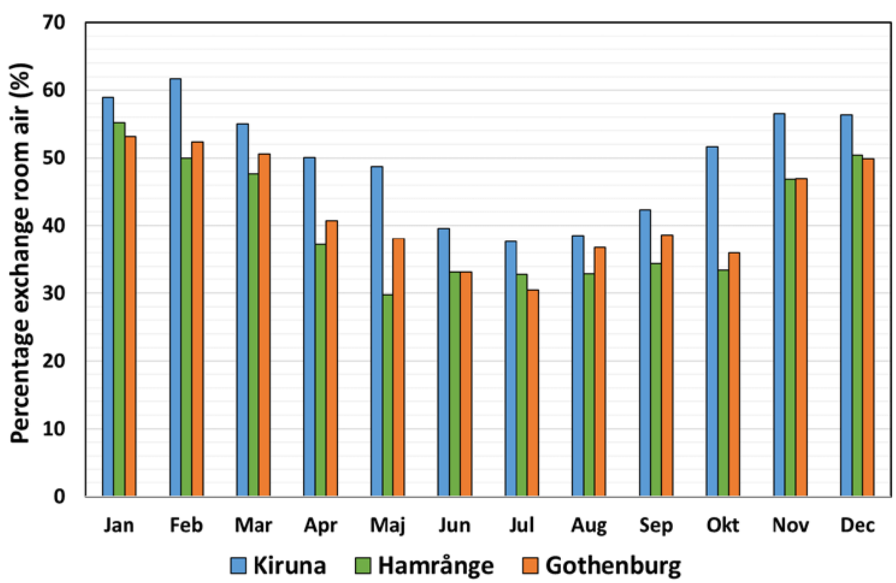

Fig. 5. Percentage exchanged room air after 1 h airing and infiltration into the main hall, averaged over the Sundays of every month.

According to Figure 5, it appears that one hour airing will cause an exchange corresponding to 30 – 60 % of the volume (monthly averaged values). Averaged over the year for each location, the results show that one hour of airing during the weekend causes between approximately 40-50 % exchanged room air in average, which is recommended after each ceremony in the church where there might have been many people and lit candles. Also, bearing in mind that special attention should also be taken to the relative humidity of the outside weather. If the indoor surface temperatures are lower than the indoor air dew-point in that occasion, there is condensation risk which might deteriorate paintings, furniture and other artifacts and therefore airing should be avoided. However, a study by Hayati [2] has shown that there is minor risk of condensation during shorter airing periods in Sweden, even in summer seasons with high relative humidity.

The annual heating of the main hall in Hamrånge church, without considering airing, is simulated as 185, 88 and 83 kWh per m^2 floor area if the church is located in Kiruna (north of Sweden), Hamrånge (mid-Sweden) and Gothenburg (south-west of Sweden), respectively. For comparison, the simulations indicate that one hour porch-airing every week (on Sundays after aggregations) in the church causes an increase in specific energy use of 2.1, 1.1 and 0.8 kWh/(m^2·year) if the church is located in Kiruna, Hamrånge and Gothenburg, respectively. There is not any statistic or questionnaire on the airing habits in churches or similar buildings; however, airing is recommended after each aggregation in order to remove the particles and moisture from people and lit candles and also because the airing effect on energy loss is negligible as increase in the specific energy due to airing is only around 1 %, as appears from the data above. The suitable duration of airing depends on many factors, such as the weather conditions outside as well the outside conditions regarding the pollutants, moisture and noise. One-hour duration is used in the current simulations in order to compare different climate regions in a cold climate such as Sweden. The simulated values are lower but of the same magnitude as the standard specific energy use additional value of 4 kWh/(m^2·year) for airing in residential buildings. However, if the number of aggregations is increased to occur on a daily basis, the specific energy use will increase by seven times and consequently the energy loss due to airing will increase to approximately 7 %.

4 Conclusion

A church model is built in the IDA Indoor Climate and Energy (IDA-ICE) simulation program with the aim of investigating the airing flow and the related energy loss. One-hour porch airing is simulated for a large single zone church building located in Kiruna (north of Sweden), Hamrånge (mid-Sweden) and Gothenburg (south-west of Sweden). The results indicate that one hour porch-airing every week (on Sundays after aggregations) during a year causes an increase in specific energy use of 2.1, 1.1 and 0.8 kWh/(m^2·year) (corresponding to only 1 % of the total heating demand) if the church is located in Kiruna, Hamrånge, and Gothenburg, respectively. That is, the heat loss is roughly two times higher in the cold climate of Kiruna. The magnitude of that heat loss is however quite small compared to the total yearly heat loss.

According to the simulations, one-hour airing results in 40-50 % (on average ranging from 30-60 %) of exchanged room air. Thus, airing seems to be a workable ventilation method in churches and similar kinds of naturally ventilated buildings, in order to introduce fresh air and evacuate contaminants emitted from e.g. people and lit candles, especially after aggregations.

Further investigations and improvements of the models used for airing are recommended as well as studying the airing habits in churches and similar naturally ventilated buildings.

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