A Study on Airing through the Porches of a Historical Church – Measurements and IDA-ICE Modelling

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ABSTRACT

In churches, intentional airing may be a measure to evacuate temporarily high levels of contaminants that are emitted during services and other occasions. Crucial contaminants include moisture and other emissions that may deteriorate and/or soil painted surfaces and other precious artefacts. Most old churches do not have any mechanical ventilation system or any purpose provided openings for natural ventilation, but the ventilation is governed by air infiltration. Enhanced airing may be achieved by opening external windows or doors. Thus, models provided in energy simulation programs should predict this kind of air flows correctly, also in order to get a proper estimation of the total energy use. IDA-ICE is examined here and the model for air flow through a large vertical opening used in the program is investigated. In the present study, field measurements were performed for airing rate in a historical church. In comparison with measured air flow rates, the simulated results were of the same magnitude, but the effect of wind direction was less considered by the simulation program.

INTRODUCTION

Air flow through large openings such as doors or windows, also called airing, is as a form single-sided or cross ventilation. Airing can be used for extracting the pollutants and refreshing the interior air especially after aggregations, i.e. occasions where there are many people and lit candles. Moreover airing can be used as a complement for mechanical ventilation at schools, for example see (Nordquist, 2002), where there are many people present at the same time and the high amount of CO_2 should be diluted. Depending on how leaky the rest of the building is, airing can be a two-way or one-way flow at the opening.

Airing is governed by buoyancy and wind effect. The temperature difference between inside and outside induce a pressure difference across the opening. But wind effect is more complicated; and not only the average wind velocity but also the turbulence in the wind also affect and induce air flows. Different models are developed for combining these effects and make a prediction of the total air flow through openings, see for example (De Gids and Phaff, 1982; Larsen and Heiselberg, 2008; Stabat et al., 2012).

IDA Indoor Climate and Energy (IDA-ICE) is a simulation program for energy usage and indoor climate for individual zones as well as the whole building. A simulated system in IDA-ICE consists of a single or multi-zone building with a primary system of chillers and boilers and air handling unit(s). Local air handing units and room units (heater/ cooler) 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 by an actual or synthetic weather file. An actual weather file in IDA-ICE consists of time (hour), air temperature (°C), relative humidity (%), wind speed (m/s)

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and direction, direct normal beam radiation (W/m²) and diffuse radiation on horizontal surface (W/m²). The models include air containing both humidity and CO_2. Moisture absorption is not included in the standard model but there are the possibilities to include moisture transfer and add a so called HMWall model at the advanced level of IDA-ICE. Airing is also modeled computationally in different energy simulation programs in order to estimate the total air flow and the energy needed to keep the expected temperature and thermal comfort. IDA-ICE can detect and handle the occurrence of opposing air flows in large vertical openings. Based on Bernoulli equation, the flow is governed by the orifice equation, so that the relationship between the flow and the pressure difference is:

$$Q = C_d A \sqrt{2 \frac{\Delta P}{\rho}} \quad (1)$$

Where C_d is the discharge coefficient (dimensionless), A is the opening area (m²), ρ is the air density (kg/m³) and ΔP (Pa) is the total pressure difference over the opening. C_d can be considered 0.61 for a sharp-edge orifice (Awbi, 2008). However in IDA-ICE the default value for C_d is 0.65 which can be changed by the user.

In general, ΔP is calculated as a summation of both wind and buoyancy induced pressures, i.e. P_w and P_s where:

$$P_w = 0.5 C_p \rho V^2 \quad (2)$$

$$P_s = -\rho g h [1 - \frac{T_0}{T_i}] \quad (3)$$

In IDA-ICE, ΔP is calculated at the bottom and top of each opening based on the pressure difference between inside and outside and the buoyancy induced pressure caused by height of the opening. The general pressure difference between inside and outside takes into account the wind induced pressure. The pressure induced by wind is calculated using the local pressure coefficient on the facade model. Thus both wind and buoyancy effects are considered in Eq. 1 for the flow through large openings like windows or doors.

Cultural heritage buildings like ancient churches are often leaky. Normally the only ventilation system in such building is natural air infiltration. There are also limited possibilities to add some mechanical ventilation or tightening in such buildings because of the esthetical and preservation aspects. There are even other concerning issues such as particle deposition and air humidity which might deteriorate the indoor materials and different pieces of art. The possibilities of implementing different climate control systems in churches is also investigated by using IDA-ICE, see for example (Napp and Kalamees, 2015). As airing is an effective solution to refresh the interior in such buildings, the models used in energy simulation program like IDA-ICE should also have an acceptable approximation of the airing rates. Thus the model used in IDA-ICE in order to predict the air flow through large vertical openings is examined in this study and the results are compared with measurements.

METHOD

The studied case is a stone church located within in Hamrånge, mid Sweden, Fig. 1. The church was erected in 1851, but has since undergone minor renovations. It constitutes a great hall with thick stone walls, plastered 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. The inner volume was assessed by 3D Laser scanning.

Table 1. Size characteristics of Hamrånge church

Location (Latitude, Longitude)	Volume (m^3)	Floor area (m^2)	Ceiling area (m^2)	Wall area (m^2)	Max ceiling height (m)	Average ceiling height (m)
Hamrånge (60°55'37"N, 17°2'20"E)	7620	695	862	1188	13.7	11.0

Figure 1 Hamrånge church.

The weather data were gained from a portable weather station, placed within one km of the church, with the weather sensor (WXT520, Vaisala Oyj, Finland) at the approximate height of the church roof. Weather data used in this study were outdoor air temperature, relative humidity, wind speed and direction, recorded at 5 min intervals. The data for solar radiation and relative humidity as well as the data for the rest of the year was gained from Swedish Meteorological and Hydrological Institute (SMHI) available at (Lundström, n.d.).

Indoor air temperature was measured using gold-sputtered NTC thermistors (Ø0.47 mm, 4 mm long) distributed at seven different heights centrally in the church hall. The height weighted average temperature is then compared with the simulated indoor air temperature with IDA-ICE.

Furthermore, tracer gas measurements were performed in the interior, the main hall of the church, in order to measure the airing rate, which later is compared with IDA-ICE simulation results. The air change rate, ACH, was measured by the tracer gas method (see e.g. ISO 12569 (CEN-European Committee for Standardization, 2012)), with SF_6 as tracer gas. The air change rate during airing an airing period was measured using tracer gas concentrations measured just before and after closing the porch and assuming an exponential decay. Three powerful mixing fans were used just before opening and after closing the porch to ensure that air was well mixed during those periods; these fans were not running while the porch was open.

The Hamrånge church was modeled and simulated in IDA-ICE simulation program version 4.6.2. There, the building is divided into six different zones, including main hall, main entrance and the tower, crawl space, sacristy, storage room and the attic room as shown in Fig. 2. The thick external walls consist of 0.85 m stone with an assumed U-value of 0.4 W/(Km^2) and the rest of the walls were taken as default walls for roof, floor and inner walls in IDA-ICE. Each window is 2.6 m times 4.7 m large and has three panes with a U-value of 1.9 W/(Km^2), solar heat gain value of 0.68 and solar transmittance value of 0.6. The side porches are 1.9 m long 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, gained from handbook data set of the Air Infiltration and Ventilation Centre. Indeed, pressure coefficients gained from a wind tunnel study were of similar magnitude.

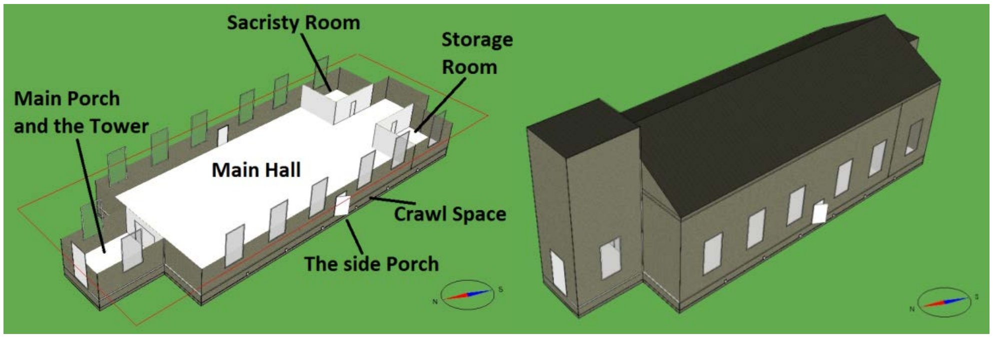

Figure 2 Hamrånge church model in IDA-ICE.

The occupancy schedule for the main hall was set as 20 people present on Saturdays from 10:00 to 12:00 and 2 people present during the rest of the days from 8:00 to 16:00 with half an hour lunch break. The activity level was assumed as 1 MET and clothing is assumed as 0.85±0.25 Clo 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 effect. The heaters were coupled with thermostats working between 15 and 16 °C. Total lighting of 2 kW and 1 kW equipment power effect was set for the main hall with the same schedule for the occupants. For sacristy and storage room 0.5 kW electric heaters as well as 0.2 W lighting was assumed.

Based on blower door tests, field observations including IR-thermography and analytical model studies it was assessed that almost 50 % of the leakage occurs through the floor, 25 % through the ceiling and 25 % through the surrounding walls of the main hall in Hamrånge church (Hayati et al., 2014). Thus the effective leakage area, approximately 0.32 m^2, gained from blower door test results are divided with the same proportion for the different parts, see Table 2.

Table 2. Leakage allocations for the main hall

Position	Azimuth	Area (m^2)	height (m)
Floor		0.160	0.0
Ceiling		0.080	11.0
Wall	70	0.015	2.0
	70	0.015	8.0
	160	0.011	5.5
	250	0.015	2.0
	250	0.015	8.0
	340	0.005	7.0
	340	0.001	7.0
	340	0.001	7.0

RESULTS AND DISCUSSION

Measurement results

The tracer gas measurement was performed during two airing experiments. As an example, the tracer gas decay preformed in the main hall of Hamrånge church for the windward case is shown in Fig. 3.

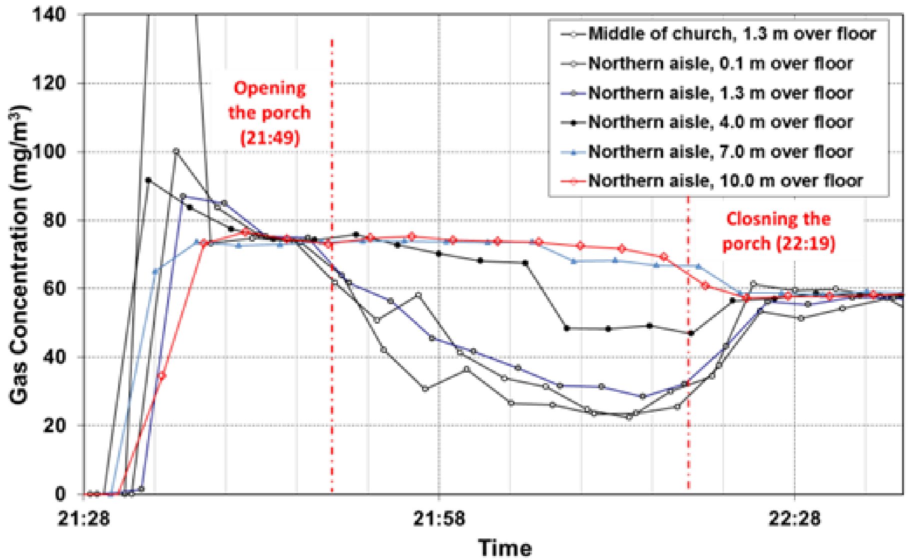

Figure 3 Tracer gas measurement in the main hall of Hamrånge church.

As can be seen in the Fig. 3, the tracer gas is well mixed just before and a few minutes after the airing period, by help of the mixing fans. The total amount of inflow is reflected in Fig. 3, i.e. including the inflow both through the porch and through the leakage located in the rest of building envelope of the main hall.

The resulting single-sided ventilation air flow rates are shown in Table 3. The performed measurements include airing values both for a Windward and a Leeward position of the open porch.

Table 3. Tracer gas measurement results and related weather parameters

Porch direction	Time of Airing			T_{in} (°C)	T_{out} (°C)	Wind speed (m/s)	Wind Incidence Angle (°)	Average Airing rate (l/s)
	From	To	Duration (min)					
Windward	21:49	22:19	30	15.3	12.2	2.4	29	**1037**
Leeward	11:48	12:13	25	15.0	12.4	2.7	188	**466**

Wind incidence angle is the wind direction perpendicular towards the facade where the side porch is located. The Wind- and Leeward cases are defined from the direction of wind relative to the porch, i.e. wind incidence angle. The table shows that the single sided ventilation flow rate for the Windward case is more than two times the flow rate for the Leeward case. The reason can be due to that for the windward case the air is pushed more freely into the church. But on the leeward side there is more turbulence and depending on the size of the vortices induced on the porch it might cause that even less flow is sucked from the building in the Leeward case.

The IDA-ICE results

The simulated ventilation rates are performed with IDA-ICE during the same airing periods as shown in Table 3. An example of measured and simulated weather parameters and air flow rates are shown in Fig. 4.

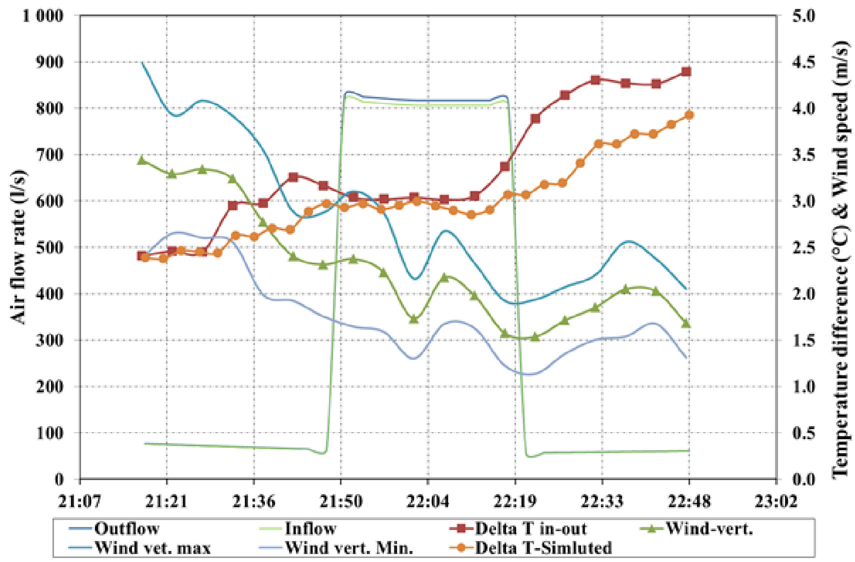

Figure 4 Weather data for airing occasion – the windward case.

The windward case is depicted in Fig. 4. “Inflow” and “Outflow” are the total flow into and out from the main hall of the church. The mean wind speed perpendicular to the façade is shown in the figure as well as the maximum and minimum vertical wind speed for the same moment to indicate the wind dynamics. “Delta Tin-out” and “Delta T-Simulated” are the measured and simulated temperature differences between inside and outside respectively. There is good agreement between the measured indoor air temperature and the one simulated by IDA-ICE, especially during the time when the door was open. As the temperature is more or less constant during the airing period but the wind decreases slightly, there is also a slight decrease in the simulated air flow rate as it shown in Fig. 4.

The simulated ventilation rates during the same airing periods as shown in Table 3 are depicted in Fig. 5 and 6. The diagrams include air in- and outflow both through the side porch and through the leakage in the rest of the building envelope. Beside the measured cases with Windward and Leeward positioned porch, the simulations include a case with No wind at all as well as a case with Fixed wind (with the fixed wind speed of 2.4 m/s and fixed wind incidence angle of 29° under the whole simulation period, not variating as in the Windward case where only the average wind speed and incidence angle under the airing period are 2.4 m/s and 29° respectively). Except the wind parameter, all the rest of weather parameters including the temperature difference are the same for all simulated cases.

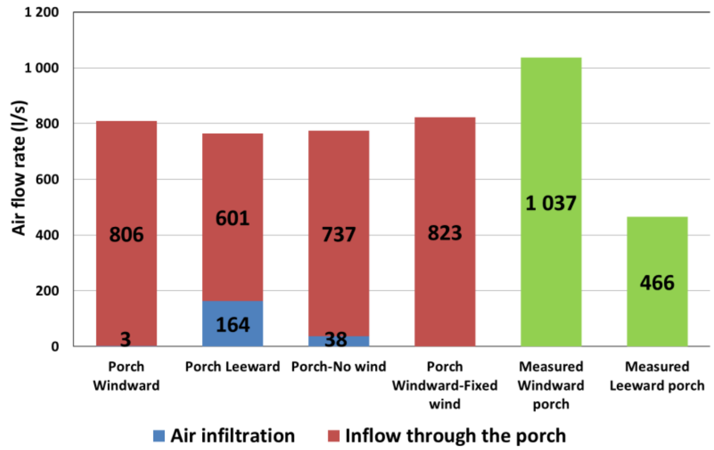

Figure 5 Air inflow to the main hall.

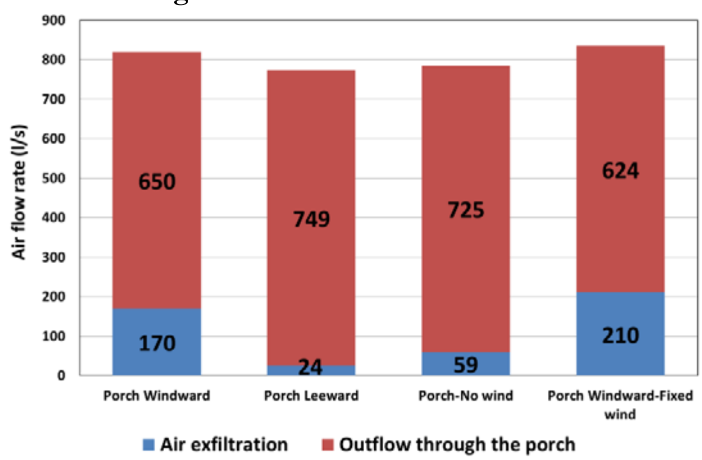

Figure 6 Air outflow from the main hall.

Fig. 5 and 6 depict the air flow into and out of the main hall including the flow both through the side porch, as well as through the leakages in the building envelope, i.e. air infiltration and exfiltration respectively. The results are from simulations, except the two green bars, showing measured total air flow rates. Apparently, the simulated total air in- and outflow results are not varying much for the different cases of Windward, Leeward, with No wind at all and with Fixed wind. This can be due to that the driving forces for airing, i.e. the temperature difference and wind speed, are not differing much. However, the percentage of air infiltration varies between different cases; air infiltration is lowest for the windward cases since flow is mostly driven through the side porch. In the Windward case air is pushed into the main hall and there is positive pressure inside which makes more exfiltration air pass through the leakages. On the other hand, with the porch on the Leeward side, air is sucked out from the main hall and there is negative pressure which makes more infiltration occurring through the leakages.

It appears that the simulated air flow rates are of similar magnitude to the measurement data, but that the simulations predict a much smaller effect of wind direction than the measurements indicate. This can be due to that the turbulence of the air in the porch area is not accounted for in the IDA-ICE model. Leakage geometry and allocation on the façades of the main hall can be another reason, since in reality it might not be identical for each surrounding façade but in the IDA-ICE model the leakage is set as identical for both siding facades, see Table. 2. Furthermore there are always degrees of inaccuracy to build a model and give the input identical to the real set-up.

CONCLUSION

A church model was built in the IDA Indoor Climate and Energy (IDA-ICE) simulation program with the aim of studying modelled air flows through large vertical openings, like doors. Locally measured weather data were used in IDE-ICE in order to be able to compare the simulation results with tracer gas measurements performed in the field. According to the simulations, airing rates were of the same magnitude as the measurement data, however the effect of wind direction was less considered in the simulations and the results tend to be less reliable for a Leeward than for a Windward positioned opening. Possible reasons might be turbulence ignorance for the air flow through large vertical openings in the model, as well as inaccuracy in the input data of the simulation model.

Further investigations and improvements of the models used for airing and air infiltration are recommended, such as implementing some coefficients regarding the turbulent effect within a large vertical opening on a building envelope.

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