Evaluation of Two Air Infiltration Models on a Church

A. Hayati[1], M. Mattsson[2] M.Sandberg[3] E.Linden[4]

ABSTRACT

Air infiltration in ancient churches and other historical and monumental buildings is of great importance considering moisture transfer, energy consumption, thermal comfort and indoor surface soiling. Two of the most established models for simulating and predicting air infiltration in buildings are the Lawrence Berkeley Laboratory (LBL) model and the Alberta air Infiltration Model (AIM-2). The applicability of these models in superimposing wind and buoyancy driven infiltration in large single zone buildings such as churches are evaluated in this study by comparing model predictions with field measurements in a 19th century stone church. Both tested air infiltration models yielded significant positive correlations between measured and predicted data, and it is concluded that the AIM-2 model works better than the LBL model for the studied church. Both models tend however to over-predict the air infiltration rate significantly. The over-predictions were larger in cases with high wind speed and it seems that the models are more fragile in wind dominated conditions. Inclusion of crawl space coefficients in the AIM-2 model improved however the predictions, especially at high wind speeds. It seems that models of the tested kind can be useful in predicting air infiltration in churches and similar buildings, but that some empirically attained model coefficients might need some adjustment to suit this kind of building better.

Keywords

Air infiltration, modeling, wind and buoyancy induced infiltration, churches, natural ventilation.

1. Introduction

The air change rate in ancient churches and other historical and monumental buildings has great energy importance when heating is required. These buildings are often leaky, and the sealing possibilities are often limited by esthetical and preservation considerations. Air infiltration also affects the indoor concentration of airborne particles, whether their major source is from indoors or outdoors. These particles cause gradual soiling of indoor surfaces. Possibilities to explain and predict the air change rate is hence of great value. Also in view of possible HVAC (Heating, Ventilation and Air Conditioning) installations, background information is needed on the current air infiltration conditions of the building, especially regarding the magnitude of the encountered natural ventilation forces.

The driving forces for air infiltration are wind, temperature difference between inside and outside (buoyancy effect) and mechanical ventilation. In the case of natural ventilation, there are only wind and buoyancy effects. Important parameters affecting the air infiltration are type, position and size of the leakage sites. In natural ventilation, the driving force is the pressure difference around openings and leakages induced by wind or buoyancy (stack effect). The buoyancy induced pressure difference is a function of the position relative to height of the neutral pressure layer, in which the pressure difference between inside and outside of the zone is zero in case of no wind [1]. There are methods for measuring the air infiltration rate in naturally ventilated buildings, but none of them can differentiate between the effect of wind and buoyancy, respectively. Instead, some analytical or semi empirical models have been developed for calculating each effect and then superimposing them to get the total air infiltration rate. But these models are always accompanied with a great deal of uncertainty, since the position and size of the leakage openings are usually impossible to measure, for example in the case of adventitious openings or leakages. Pressurization tests can give a value of the total leakage area at a reference pressure, e.g. the so-called effective leakage area, *ELA*, although uncertainties due to wind and buoyancy effects need to be considered carefully for this large type of buildings [5]. The air change rate can be gained by tracer gas concentration decay method [4], and IR-thermography and some other leak identification methods can be helpful in getting an idea of the leakage distribution in the building envelope [3]. The information gained from these methods can be used in the semi-empirical and analytical models. A problem in superimposing the wind and stack effect is that the wind induced flow and the flow due to the temperature difference (stack effect) cannot be superimposed in a linear way [8].

Using single zone models are easier in comparison with multizone models because the assumption in single zone models is that the whole volume of the zone is well mixed, and only one temperature is used for the inside temperature. Multi zone models instead need to consider different pressures and temperatures in the zones [9].

1.1. Single Zone Air Infiltration Models

The two most established and referred to single zone models (which were developed to simulate and predict infiltration rates of the buildings) are the Lawrence Berkeley Laboratory (LBL) model and the Alberta air Infiltration Model (AIM-

1 University of Gävle, Sweden, abolfazl.hayati@hig.se
2 University of Gävle, Sweden, magnus.mattsson@hig.se
3 University of Gävle, Sweden, mats.sandberg@hig.se
4 University of Gävle, Sweden, Elisabet.Linden@hig.se

2) [1]. It is however uncertain how applicable these models are for churches, which are large (high), leaky and often particularly wind exposed. They also show a great variety in the distribution of air leakages: floor, ceiling and façade (windows & porches) may all constitute a totally dominating leakage site, depending on the construction of the church.

One of the first single zone models presented was the Lawrence Berkeley Model (LBL) [6]. Later on, the Alberta Air Infiltration Model (AIM-2) was developed by Walker and Wilson [7], however based on the LBL model. A short introduction of each model is given here.

1.1.1. The Lawrence Berkeley Laboratory (LBL) model

The LBL model is based on the assumption that a building has a cuboid shape. The model needs information from a pressurization test as well as estimation about the leakage distribution. In this method, the air infiltration due to wind and stack are calculated independently and then combined in a quadrature way:

$$Q_t = [Q_w^2 + Q_s^2]^{\frac{1}{2}} \quad (1)$$

Where Q_w is the wind induced infiltration term and Q_s is the buoyancy (stack) induced infiltration term.

Each infiltration term is calculated by means of air leakage distribution parameters R and X, given by:

$$R = \frac{(A_c + A_f)}{A_o} \quad (2)$$

$$X = \frac{(A_c - A_f)}{A_o} \quad (3)$$

Where A_c is the area of ceiling leakage (m^2); A_f is the area of the floor leakage (m^2); and A_o is the total effective leakage area of the building (m^2).

The effective leakage area, A, can be estimated from a building pressurization test – yielding a power law equation for the leakage characteristic – and from the orifice opening leakage formula:

$$Q = A\sqrt{\frac{2\Delta P}{\rho}} \text{ (Flow through orifice opening)} \quad (4)$$

$$Q = K(\Delta P_{ref})^n \text{ (Power law equation)} \quad (5)$$

Total effective leakage area, A_o, is given by rearranging (4) and (5):

$$A_o = \frac{K(\Delta P_{ref})^n}{\sqrt{\frac{2\Delta P_{ref}}{\rho}}} \quad (6)$$

Where n is the flow exponent and K is the flow coefficient gained from a pressurization test; ΔP_{ref} is an arbitrary reference value of the indoor-outdoor pressure difference, usually chosen as 4 Pa. Inserting this value in the above equation for the effective leakage area yields:

$$A_o = \frac{K(4)^n}{\sqrt{\frac{8}{\rho}}} \quad (7)$$

The buoyancy (stack) induced infiltration, Q_s, is estimated from:

$$Q_s = f_s^* A_o \sqrt{(\Delta T)} \quad (8)$$

Where ΔT is the temperature difference (K) between inside and outside and the reduced stack factor, f_s^*, is given by:

$$f_s^* = \left[\frac{1 + 0.5R}{3}\right](1 - \left[\frac{X^2}{(2 - R)^2}\right])\sqrt{gH/T_i} \quad (9)$$

Where T_i is the internal temperature (K), g is the gravitational constant (ms-2) and H is the ceiling height (m).

The **wind induced air leakage** is estimated from:

$$Q_w = f_w^* A_o U' \quad (10)$$

Where U' is the wind speed measured at a weather station (m/s) and f_w^* is the reduced wind factor, which in turn can be estimated from:

$$f_w^* = C' \sqrt[3]{(1 - R)} [\alpha \left(\frac{H}{10}\right)^{\gamma} / (\alpha' \left(\frac{H'}{10}\right)^{\gamma'}) \quad (11)$$

Where C' is the generalized shielding coefficient; see table 1. α and γ are terrain parameters and they depend on the terrain class; see table 2.

Shielding class	C'	Description
I	0.34	No obstruction or local shielding whatsoever
II	0.30	Light local shielding with few obstructions
III	0.25	Moderate local shielding, some obstructions within two house heights
IV	0.19	Heavy shielding, obstructions around most of perimeter
V	0.11	Very heavy shielding, large obstruction surrounding perimeter within two house heights

Table 1: Shielding coefficient used in the LBL model [6]

Class	γ	α	Description
I	0.10	1.30	Ocean or other body of water with at least 5 km of unrestricted expanse
II	0.15	1.00	Flat terrain with some isolated obstacles (e.g. buildings or trees well separated from each other)
II	0.20	0.85	Rural areas with low buildings, trees, etc.
IV	0.25	0.67	Urban, industrial or forest areas
V	0.35	0.47	Center of large city

Table 2: Terrain parameters for standard terrain classes [6]

1.1.2. The Alberta air Infiltration Model (AIM-2)

The Alberta air Infiltration Model (AIM-2) was developed for single zone buildings. In AIM-2, like in the LBL model, numerical solutions are used for solving algebraic equations for mass conservation of the wind and buoyancy (stack effect) induced air infiltration flows. For each infiltration term, the power law equation is used for calculating the air flow from the pressure difference between inside and outside and the resulting flows are combined in a quadratic form including an interaction term with an empirical constant.

The basic data used in the model are: flow coefficient and flow exponent gained from pressurization test, building height, the temperature inside and outside, wind velocity and the leakage distribution indicated by the power law flow coefficient.

The infiltration rate induced by stack effect as well as the pressure due to each term can be attained with the following equations [7&8]:

$$\Delta P_s = \rho_{out} g H \frac{|T_{in} - T_{out}|}{T_{in}} \tag{12}$$

$$Q_s = C f_s (\Delta P_s)^n = C f_s [\rho_{out} g H \frac{|T_{in} - T_{out}|}{T_{in}}]^n \tag{13}$$

Where Q_s is the buoyancy induced infiltration rate (m^3/s); C is the flow coefficient ($m^3/(sPa^n)$); n is the flow exponent; f_s is the stack factor; ΔP is the indoor-outdoor pressure difference (Pa); ρ_{out} is the density of outside air (kg/m^3); g is the gravitational constant (m/s^2); H is the ceiling height of the building (m) and T is the temperature of air (K). Further defined:

$$\Delta P_w = \frac{\rho_{out} (S_W U)^2}{2} \tag{14}$$

$$Q_w = C f_w (\Delta P_w)^n = C f_w [\frac{\rho_{out} (S_W U)^2}{2}]^n \tag{15}$$

Where Q_w is the wind induced infiltration rate, f_w is the wind factor; S_W is a dimensionless shelter coefficient to estimate local shielding (given in table 3) and U is the wind speed measured at the eaves height of the building (m/s).

The stack factor f_s and wind factor f_w are functions of the leakage distribution factor and the flow exponents.

AIM-2 distinguishes between two cases: with and without the existence of flue(s). The air leakage is divided into leakage from floor, walls, ceiling and flue, respectively. The leakage distribution of the building envelope is introduced by assigning a flow coefficient to each of these building parts: floor (C_f), walls (C_w) ceiling (C_c) and flue (C_{flue}). The sum of these flow coefficients should equal the total flow coefficient C_o:

$$C_o = C_f + C_c + C_w + C_{flue} \tag{16}$$

Further, leakage distribution parameters R, X, and Y are defined as follows:

$$R = \frac{C_f + C_c}{C_o + C_{flue}} \tag{17}$$

$$X = \frac{C_c - C_f}{C_o + C_{flue}} \tag{18}$$

$$Y = \frac{C_{flue}}{C_o + C_{flue}} \tag{19}$$

The calculation of stack and wind factors depend on whether flue(s) exist or not, and for each case there are some separate formulas. For cases without flue, the wind and stack factors are as follows:

$$f_w = 0.19(2-n)(1 - \left(\frac{X+R}{2}\right)^{3/2}) \tag{20}$$

$$f_s = (\frac{1+nR}{n+1})(\frac{1}{2} - \frac{1}{2}\left(\frac{X^2}{2-R}\right)^{5/4})^{n+1} \tag{21}$$

For a house with crawl space and flue, there is another formula for the wind factor, in which the pressure inside the crawl space is determined by the average pressure coefficient of the four walls, which leads to the following equations [7]:

$$f_{wc} = 0.19(2-n) X^* R^* Y^* \tag{22}$$

Where

$$R^* = 1 - R(\frac{n}{2} + 0.2) \tag{23}$$

$$Y^* = (1 - \frac{Y}{4}) \tag{24}$$

$$X^* = 1 - ((\frac{X - X_s}{2-R})^2)^{0.75} \tag{25}$$

$$X_s = (\frac{1-R}{5}) - 1.5Y \tag{26}$$

The following table can be used for values of the wind shelter coefficient S_W:

Shelter Coefficient Sw	Description
1.0	No obstructions or local shielding
0.9	Light local shielding with few obstructions within two house heights
0.7	Heavy shielding, many large obstructions within two house heights
0.5	Very heavy shielding, many large obstructions within one house height
0.3	Complete shielding, with large buildings immediately adjacent

Table 3: Estimates of wind shelter coefficient for the case of no flue [7]:

Through the above formulas the infiltration rates due to the wind, Q_W, and stack effect, Q_s, can be determined, and combining them by the following formula gives the total air infiltration, Q_t.

$$Q_t = [Q_W^{\frac{1}{n}} + Q_s^{\frac{1}{n}} + \beta (Q_s Q_W)^{1/2n}]^n \tag{27}$$

Where β is an empirical constant set to -0.33 [8]. The leakage distribution factors for the wall, ceiling, floor and flue need to be estimated by visual inspection or other methods (there is a range of typical values given by ASHRAE [1]).

1.2. Comparison between LBL and AIM-2

The AIM-2 has some main differences in comparison with LBL: (1) In AIM-2 the attic space and the floor above crawl space have their own pressure coefficients, while in LBL their pressure coefficient is considered to be zero; (2) in AIM-2 the flue is considered separately but in LBL there is no possibility for separate leakage treatment due to flue; (3) superposition method in AIM-2 is done by using the flow exponent (*n*) gained from a pressurization test, whereas in LBL the superposition method is done by setting which corresponds to the orifice flow assumption (flow through large opening); and (4) an interaction term is included in AIM-2 for combining the wind and stack induced air infiltration, whereas the superposition method in LBL is according to a simple quadrature method [7].

Both models are sensitive to the estimation of the values for the leakage parameters and it is very difficult to do this for each part of the building, i.e. of walls, floor and ceiling. One way could be to seal all building parts except the one of interest and perform a pressurization test, but in the case of large single zones such as big churches, it is very difficult to execute such a method. So choosing values of the leakage distribution parameters is a source of great uncertainty in such models, as is converting measurement values for the wind at the place of a weather station to the location of the building. The latter problem can be reduced by site measurement of the wind velocity.

Walker and Wilson [8] compared different single zone models including linear addition, Pressure addition, Quadrature (i.e. LBL model) and AIM-2; and they recommended using (1) i.e. the LBL model for the sake of simplicity and reliability. They used air change rate data of two test houses with 3.7 m height located in Edmonton, Canada; they found that both AIM-2 and LBL methods have maximum errors of 10 % while simple linear addition of the flows can have errors of up to 50 % [8].

Liddament and Allen [2] compared different air infiltration models including the LBL model (but not the AIM-2 model). They assessed likely inaccuracies due to measurement and input data and they considered that if the model predictions are in the range of ±25 % of the measured data, then the results are in an acceptable range. They compared model predictions with measurements in different houses in different locations within Swiss, Canada and UK; they found that the LBL model results were in good agreement with the measured data, and that more than 81 % of the results were within the acceptable 25 % of the measurement values [2]. An example of LBL model results for a two story timber frame house is shown in figure (1).

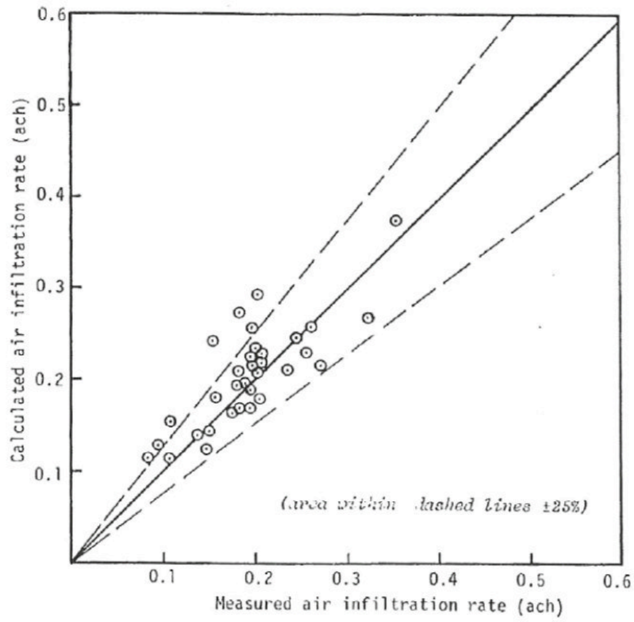

Figure 1 The LBL model prediction results versus the measured air infiltration rate [2].

In another study [9] AIM-2 was evaluated against measurement data of 16 detached houses in Ottawa, Canada in which 15 of them had at least one flue. It was found that AIM-2 prediction results of air infiltration rate were in better agreement with the measurement data and yielded an absolute relative error of 19%, while the LBL model on average yielded an error of 25 %. The absolute relative error is the absolute value of the difference between the measured and predicted values of air change rates divided by the measured value. In AIM-2, 38 % of the air infiltration rates were predicted with a relative error of less than 10 % while in the LBL model, just 29 % of the data were predicted with relative error of 10 %. On average, AIM-2 had a relative error and an underestimation of the air change rates by 5% while LBL had an overestimation of air infiltration rates by 7-15 %. The study showed that the results were changing from house to house and were highly sensitive to the input data.

In this study the LBL and AIM-2 air infiltration models are examined for their prediction of the air infiltration rate for a big church which can be considered as a large single zone, and the model prediction results are evaluated and compared with the field measurements. The models differ in complexity, and the aim of this study is to find out which model yields the best predictions and how precise the models are in the case of large single zones like a church; results on this issue hardly seems to have been presented before.

2. Method

Depressurization tests were run two different times for a church located in Hamrånge, Sweden. The church has a volume of 7620 m^3, floor area of 695 m^2 and ceiling height of 13.7 m. The volume was measured by 3D Laser scanning method. Flow exponent and flow coefficient attained at a blower door test (depressurization) were used as input in the discussed models.

Weather data were gained from a mast located within 1 km of the church, so there was no need to convert the measured wind data, because the measurement position was close enough to the church. Inside temperature was measured at different heights and the height weighted average was used as the inside temperature in the calculations.

The air change rate at normal condition was measured by the concentration decay method by spreading SF_6 gas in the church and analyzing the decay of its concentration. More details on these measurements can be found in [4]. Air change rate data were attained at three different occasions in May, June and October of 2010. For the calculation of the air change rate, one hour averages of the data were used for May and two hour averages of the data were used for the cases of June and October. The standard uncertainty for the tracer gas concentration slope of the measured data was calculated.

The required input data for calculating the wind and buoyancy driven flow rates were put in the corresponding equations of (8) and (10) in case of LBL model and (13) and (15) for case of AIM-2; and the resulting flow rates were put in the relating superposition equations of (1) and (27) in order to get the total predicted flow rates. In the case of the AIM-2 model, two different wind factors were used: one considering the crawl space, i.e. (22), and the other one not considering crawl space, i.e. (20). Furthermore, the measurement data were classified into wind and buoyancy dominated ones, respectively, in order to check if modeling performance differed between these regimes.

Moreover, two different assumptions of the leakage distribution at the building envelope were tested; one assuming even distribution and the other assuming floor-dominating leakage. The latter assumption was based on previous studies in Hamrånge church [3], which pointed to the wooden floor as the major leakage area. This could be found out by using a couple of different leakage identification techniques, including IR-thermography and tracer gas techniques.

3. Results

The pressurization test was done during a day in August, yielding a flow exponent of 0.64 and a flow coefficient of 550 $l/(sPa^{0.64})$. The result consists of two major categories: the reference case with homogeneous leakage assumption and a "guesstimated" leakage case. For each category the model predicted air change rates are depicted versus the measured data at the same time. The guesstimated leakage category is in turn divided into four different subdivisions; the first part is the general one containing the whole data set, shown in figure 3; the second part is the buoyancy dominated data over the whole time span of the measured data, shown in figure 4; the third case is the wind dominated range of data, shown in figure 5; and the last part is called the intermediate case in which neither buoyancy nor wind forces dominate, shown in figure 6. Each diagram includes the LBL model, the AIM-2 model excluding the crawl space and the AIM-2 model including the crawl space.

3.1. The reference case

In the reference cases, the leakage is considered evenly distributed over the building envelope of the church, resulting in 31.4 % of the leakage assigned to the ceiling, 25.3 % to the floor and 43.3 % to the walls.

A diagram comparing the predicted values with measured values for the reference case is shown in figure 2. Least-squares regression lines are included, as well as values of the squared Pearson product-moment correlation coefficient, R^2.

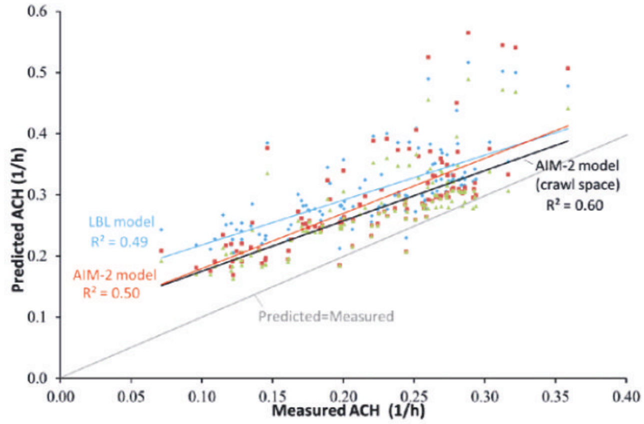

Figure 2 Measured vs. predicted ACH; evenly distributed leakages assumed.

Apparently the models tend to over predict the air change rate; the median over-prediction is 39 % for LBL, 29 % for the AIM-2 (*excluding* crawl space) and 24 % for AIM-2 (*including* crawl space). The latter thus tends to predict best, and it also has the highest R^2-value: 0.60.

3.2. Guesstimated leakage distribution

So far an even leakage distribution in the building envelope has been assumed. However, by using some leakage identification techniques [3] an educated guess about a more realistic leakage distribution could be made. This pointed to the wooden floor as the major leakage point. Building pressurization tests with covered vs. uncovered crawl space vents verified this indication. A *guesstimated* more accurate leakage distribution was thence tested on the air infiltration models, implying 50 percent of the leakage attributed to the wooden floor, 25 % to the ceiling and 25 % to the walls. Results on the measured vs. predicted air change rates are depicted in Figure 3.

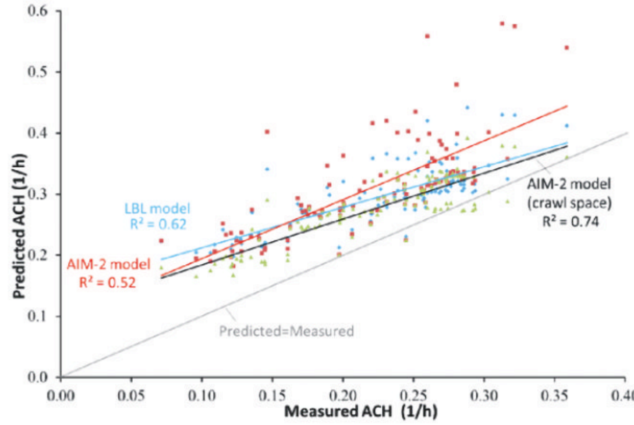

Figure 3 Measured vs. predicted ACH; guesstimated leakage distribution.

In this case, the median of the over-prediction is 33 % for LBL, 39 % for the AIM-2 model (*excluding* crawl space) and 25 % for the AIM-2 model (*including* crawl space). The AIM-2 model including crawl space has better results and highest R^2-value: 0.74.

A general over-prediction by the air infiltration models is indicated above. In order to investigate the reasons for this over-prediction, subsets of data were analyzed, with the relative importance of the two infiltration-driving forces – wind vs. buoyancy – as the categorizing criteria. The measurement data were thus categorized as being wind-dominated when the quotient between equations (14) and (12) was greater than 2, whereas they were categorized as being buoyancy-dominated when that quotient was less than 0.5. Data falling within the quotient limits 0.5 and 2 were categorized as belonging to an intermediate case, being neither wind nor buoyancy dominated. Scattergrams with regressions for these subsets of data are shown in Figures 4, 5 and 6.

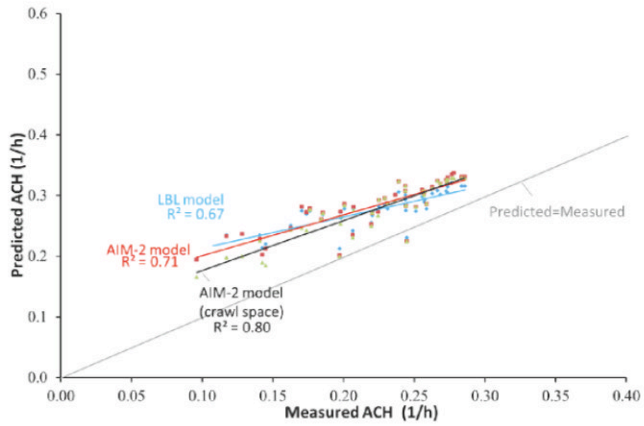

Figure 4 Measured vs. predicted ACH; guesstimated leakage distribution, buoyancy dominated data.

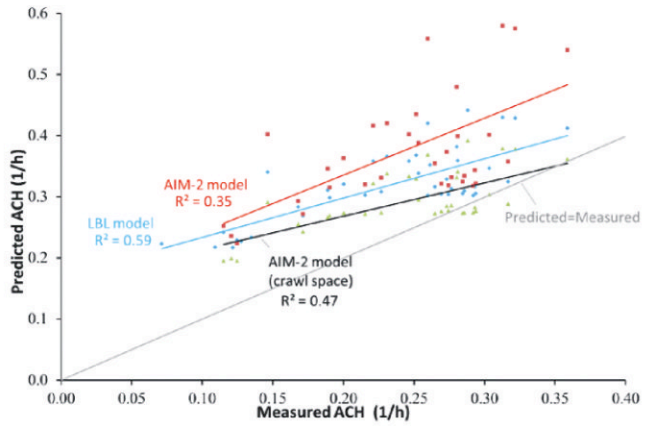

Figure 5 Measured vs. predicted ACH; guesstimated leakage distribution, wind dominated data.

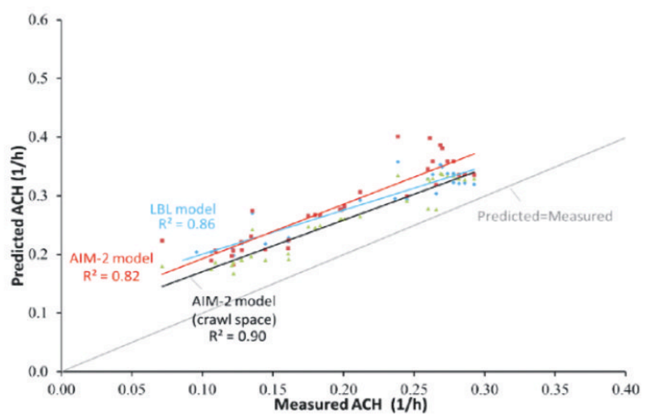

Figure 6 Measured vs. predicted ACH; guesstimated leakage distribution, intermediate case

Figure 4 shows similar prediction performance of the three models for the buoyancy dominated data, with fairly high correlations (R^2) values but still some over-prediction. In contrast, Figure 5 indicates many more difficulties in predicting the wind dominated data, and it seems to be in this case that inclusion of crawl space parameters considerably improves the predictions. The intermediate case, Figure 6, yields the best correlations, but also here there is a significant over-prediction.

In all cases (of evenly distributed and guesstimated leakage estimations) except for the wind dominated ones, the AIM-2 model (including crawl space) has a greater correlation of data and higher R^2-value in comparison with the LBL model. In wind dominated cases, LBL model has a better correlation of data and it can capture the effect of strong winds better than the AIM-2 model. In general AIM-2 (including crawl space assumption) has up to 25 % better results of air change rates, in all cases excluding the wind dominated case. In the wind dominated case the LBL model has up to 43 % better correlation of data (considering R^2-values). Both models have the highest R^2-values in the intermediate case, i.e. the case when none of the driving forces are dominant, in another word the models are most effective while the driving forces are more or less in the same range. On the other hand, the wind dominated cases have the worst correlation and R^2-values, which shows that the models are not powerful enough to capture the effect of high winds.

In the case of the guesstimated leakage distribution, both models have improved results in comparison with the reference case. Comparing the R^2-values of diagrams 2 and 3, the LBL model and AIM-2 model have up to 28 % and 24 % better predictions, respectively. Both models have higher R^2-values in the intermediate case and then for the stack dominated case.

4. Discussion

Considering the church in this study, the present results show that all air infiltration models tested yield over-prediction of the air change rate. The reason for model over-predictions might be due to that the equations cannot capture the buoyancy and wind effect properly in such large and high zones like a church, while the models were designed for the dwellings using data from normal residential houses with a 3 m height [7]. Misfit by the models can also be due to the fact that the interaction term used in AIM-2, equation (27), is not good enough for large single zones and it should be modified for such zones. The current interaction term () was reached by fitting the equation (27) on some measured air change rate data from six test houses located in Edmonton, Canada [8]. The current case is a bit special in that most of the leakage appears to occur at the floor, while the enclosing walls seem to be relatively tight. In such a case the wind can be expected to be less influential, and indeed the models show the most over-prediction for the wind dominated data. The cause of the model over-predictions appear however not to be uncertainty in measured data, because the average uncertainty of the individual measured air change rates was 9 %, which is quite low.

Using the special wind factor for the houses with crawl space, i.e. (22), improved the model predictions (less errors) in comparison with using the normal wind factor, i.e. (20). As can be seen in diagrams 2 to 6, in general the AIM-2 model (including crawl space) has the best results i.e. the over-prediction of air change rates is less for the AIM-2 case taking into consideration the special wind factor for the houses with crawl space. Furthermore, as regards crawl space, the correlation between data is improved by up to 45% in the case of the guesstimated leakage distribution and by 20 % in the case of evenly distributed leakage assumption. Another improvement – however difficult – in the models could be to consider the type and position of each leakage site and not only a total value for different parts of the enclosing area, as in the LBL and AIM-2 models.

In comparison with the previous studies discussed in the introduction, the present model results seem more scattered and show more over-predictions, for instance in comparison with figure (1) [2]. It is possible that the empirically attained model coefficients need some adjustment for churches and similar buildings. However, more statistics for this kind of buildings are needed. It is also shown e.g. by Wang et al. [9] that AIM-2 model results change from house to house. The present study was carried out only in one church, and the next stage in this project is to obtain similar data from more churches.

The model predictions are dependent on the leakage distribution parameters, and it is impossible to make a precise estimation of these, especially when much of the leakages are of the adventitious type. In the present case, several leak identification techniques (described by [3]) were found useful and gave guidance in guestimating a likely leak distribution. Especially a complementing fan pressurization test with crawl space vents covered justified the assignment of high leakage percentage to the floor. Still, some remaining uncertainty in the leakage distribution is acknowledged. Introducing parameters based on certain leakage identification methods reduced the median over-prediction by 15 % for the LBL model, but, surprisingly, almost not at all for the AIM-2 model (crawl space version). This suggests that the model sensitivity to the assumed distribution is relatively small.

Another source of uncertainty in this study is the model assumption of cuboid buildings while the inside zone of the church studied, in reality has a semi cylindrical vaulted section in the middle of the ceiling. In the model calculation above, the maximum ceiling height was used. However, a repeated calculation with a corrected ceiling height indicated only a minor effect on the results. Other parameters affecting the uncertainty include leakage parameters, temperature measurement, blower door method, the pressure difference, wind velocity measurement and wind sheltering by the surrounding terrain.

The temperature difference between the floor and the ceiling was up to three degrees, with stronger stratification closer to the floor. Inside temperature was measured at different heights and the height weighted average was used as the inside temperature in the calculations. Mattsson et al [5] have found that this magnitude of temperature stratification is small enough to justify using the height weighted average temperature as regards buoyancy induced pressures in this kind of buildings.

Currently, there is only depressurization data since the weather conditions (wind) at a performed pressurization test were too troublesome. The intention is to repeat this test in the future. However, differences in pressurization/depressurization tests due to flexing in the building materials appear likely to be small in old stone churches.

5. Conclusions

Both tested air infiltration models yielded significant positive correlations between measured and predicted data, and it is concluded that the AIM-2 model works better than the LBL model for the studied church, Hamrånge. Both models show however a significant over-prediction. The over-prediction of the results was larger in cases with high wind speed and it seems that the models are more fragile in wind dominated conditions. Inclusion of crawl space coefficients in the AIM-2 model improved however the prediction, especially at high wind speeds.

It is difficult to estimate the leakage distribution parameters that the models are dependent on. The introduction of the guestimated, more likely distribution increased the data correlation but a little surprisingly, did not improve the model predictions significantly. The results indicate that the empirically attained model coefficients might need some adjustment for churches and similar buildings.

6. Acknowledgments

Our thanks to the Swedish Energy Agency for project funding.

7. References

[1] HEATING, A. S. O. & OWEN, M. S. 2009. 2009 ASHRAE Handbook: Fundamentals CHAPTER 16: Ventilation and Infiltration. American Society of Heating, Refrigeration and Air-Conditioning Engineers.

[2] LIDDAMENT, M. & ALLEN, C. 1983. The validation and comparison of mathematical models of air infiltration, Air Infiltration Centre.

[3] MATTSSON, M., LINDSTRÖM, S., LINDEN, E. & SANDBERG, M. Methods to Identify Air Leakages in the Building Envelope of Churches. EEHB 2011: Conference on Energy Efficiency in Historic Buildings, 2011a.

[4] MATTSSON, M., LINDSTRÖM, S., LINDEN, E. & SANDBERG, M. 2011b. Tracer Gas Techniques For Quantifying The Air Change Rate In Churches – Field Investigation Experiences. Proc. Roomvent 2011: 12th International conference on air distribution in rooms. Ed. Hans Martin Mathisen. Paper No 235. ISBN: 978-82-519-2812-0. Trondheim, Norway.

[5] MATTSSON, M., SANDBERG, M, CLAESSON L., LINDSTRÖM, S. 2013. Fan pressurization method for measuring air leakage in churches – wind and stack induced uncertainties. Conference: 3rd European Workshop on Cultural Heritage Preservation (EWCHP), Bozen, Italy.

[6] SHERMAN, M. & GRIMSRUD, D. T. MEASUREMENT OF INFILTRATION USING FAN PRESSURIZATION AND WEATHER DATA. Proceedings, 1980. Air Infiltration Centre, 277.

[7] WALKER, I. S. & WILSON, D. J. 1990. AIM 2: The Alberta air infiltration model. *University of Alberta, Department of Mechanical Engineering Report* 71.

[8] WALKER, I. S. & WILSON, D. J. 1993. Evaluating models for superposition of wind and stack effect in air infiltration. *Building and Environment*, 28, 201-210.

[9] WANG, W., BEAUSOLEIL-MORRISON, I. & REARDON, J. 2009. Evaluation of the Alberta air infiltration model using measurements and inter-model comparisons. *Building and Environment*, 44, 309-318.