Development of a Numerical Air Infiltration Model Based On Pressurization Test Applied On a Church

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ABSTRACT

Pressurization (blower door) test is a well-established standardized method, performed in order to quantify the total leakage in a building envelope. However, blower door results are not adequate to use when air leakage through the building envelope during natural conditions (non-pressurized) is to be estimated. A common assumption made when estimating air leakage during natural conditions, is that air leakage paths are evenly distributed in the areas of the building envelope. This assumption gives quite poor calculation results since different leakage configurations are often situated unevenly in the envelope. In order to improve the correspondence between Blower door and air leakage model results, more information on the types and locations of the leakage paths are required as input to simulation models.

This paper investigates if additional information from visual inspection and IR-thermography observations at site can increase the precision when simulating air change rates due to air leakage in natural conditions. A numerical model is developed in this study by allocating leakage in various parts of the building envelope. The leakage allocation is based on visual inspection and IR-thermography observations at the site during the blower door test.

This procedure is tested in the case study of a large single zone church. Blower door, neutral pressure level measurement and leakage allocation results are used as input in the numerical model. Model results are compared with tracer gas measurements and result accuracy is compared with results from the Lawrence Berkeley Laboratory model (LBL) and the Alberta Air Infiltration Model (AIM-2) for the same church.

INTRODUCTION

Air leakage or air infiltration is the unintended outdoor airflow into the building through the adventitious leakages in the building envelope, such as cracks, seams, holes in joints or sealing and also through the normal use of exterior doors for entrance or egress (ASHRAE, 2013). Air infiltration is governed by the magnitude of pressure difference between inside and outside the building, caused by the mechanical ventilation, wind and buoyancy (stack effect). Infiltration flow also depends on the position of the leakage in the building envelope and in relation to the position of the neutral pressure layer (NPL), at which there is no pressure difference. Moreover, airflow through a certain opening also depends on the characteristics of the opening including the shape and size (ASHRAE, 2013). Due to the complex nature of infiltration, it is common to measure leakage performance of a building by pressurization tests and then extrapolate the data to gain the air leakage during natural conditions. Further analysis of the infiltration rates during natural conditions can also be based on the semi-empirical models like Lawrence Berkeley Laboratory model (LBL) (Sherman & Grimsrud, 1980) and the Alberta Air Infiltration Model (AIM-2) (Walker & Wilson, 1990), which are based on input from pressurization tests.

Pressurization test, also called blower door procedure, is a standardized method for measuring a total value of the air leakage at a reference pressure (EN13829, 2000). The building is pressurized with a fan while measuring the

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flow rate. The relationship between sampled flow values and pressure difference is the so called power law equation:

$$q = C_L . \Delta p^n \quad (1)$$

C_L is the airflow coefficient and n is the flow exponent. These two parameters are the leakage characteristics of the building and also the basis for obtaining the following leakage quantities:

- Air leakage rate at a reference pressure difference, usually 50 Pa (q_{50}),
- Air change rate at reference pressure difference, usually 50 Pa (ACH_{50}),
- Air permeability; air leakage rate at the reference pressure difference divided by the enclosing building envelope area,
- Effective Leakage Area, ELA; equivalent leakage area occurring at a reference, normally 4 Pa, pressure difference between inside and outside, see for example (ASHRAE, 2013)

The pressure difference of 4 Pa may be a more realistic pressure difference to use in comparison with 50 Pa, since pressure differences rarely exceed 10 Pa in naturally ventilated buildings (Etheridge, 2011). Therefore, it is common to calculate air leakage at 4 Pa to estimate air leakage flow in natural conditions. However, uncertainties in estimating ELA at lower pressure differences, using the leakage characteristics result of a blower door test, are large (Mattsson et al., 2013).

In case of natural ventilation, the indoor pressure is dependent on the combination of the buoyancy and wind pressures. The total pressure difference between inside and outside is a nonlinear combination of the two effects (Walker and Wilson, 1993). There are some analytical and semi-empirical models developed for combining buoyancy and wind effects. Two well-established models for predicting air infiltration rates in single zone buildings are the LBL and AIM-2 models. Both use input from a blower door test. Similar to these, basic and enhanced models presented in ASHRAE Fundamental handbook, also require input from a blower door test and assessed coefficients related to building height, leakage distribution and wind sheltering (ASHRAE, 2013). A summary of single zone infiltration models is given by Hayati et al. (2014). Based on the fact that the wind and buoyancy induced pressure difference depends on the leakage position in the building envelope, Sherman (1992) studied various models and found that the accuracy of such models depends on the leakage distribution between the floor, ceiling and surrounding walls. Air infiltration flow also depends on the size and position of the leakage in the surrounding envelope. To get an overall picture of the leakage distribution, different leak identification methods can be used, such as IR-thermography. However, this issue is not covered with the blower door method; the building is pressurized without pointing out the nature of and where leakages are distributed - only a total value of the air infiltration rate and/or power law equation is gained. For example, a building with a leakier floor might have the same blower door results as a similar building with leakier façades, but have totally different infiltration flows in natural conditions. The lack of identifying and characterizing the distribution of leakages in pressurization methods is clear though there is ongoing research with the purpose of assessing more information on leakage paths at site, see for example (Dufour et al., 2009).

This study attempts to show how on-site observations (audit and IR-thermography) may be used to improve modelling airflows in natural conditions on basis of blower door test results and a measurement of NPL in natural condition. Other models, as previously mentioned, require that the measured flow is distributed among the floor, ceiling and walls by means of “guesstimation” (Hayati et al., 2014). The idea here is to enter observed leakages, each modelled with Poiseuilles equation, in a numerical one zone model on a crawl space. The input data is then processed to give a good fit to blower door data and NPL for the corresponding measurement conditions. Finally, natural condition simulations are preformed and compared with tracer gas measurements, with the ambition of improving result accuracy in comparison with LBL and AIM-2 model results for the same church.

METHOD

Measurements

The studied case is a stone church located within Hamrånge, mid Sweden, Figure 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 sides; these structures are airtight. Gable roofs and inner ceilings 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 (with bars) and weather-stripped. Each side of the church has double outer doors to enter the large hall. There is a crawl space underneath a wooden floor; the floor consisting of double boards with a ~15 cm layer of lime sand in between. Crawlspace walls have equidistant apertures to cross-ventilate the space. The church is naturally ventilated through leakages in the envelope. Size characteristic is 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. 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

Outdoor air temperature and wind speed were recorded at 5 min intervals with a portable weather station (WXT520, Vaisala Oyj, Finland) at the approximate height of the church roof. Indoor air temperature was measured using NTC thermistors (Ø0.47 mm, 4 mm long) distributed at seven different heights centrally in the church hall. Analysis of the impact of noted temperature stratification proved this to have an insignificant effect on the vertical variation of the indoor outdoor pressure difference, (Mattsson et al., 2013).

Figure 1 Hamrånge church. Note the door in the middle of the wall.

Two sets of Blower Door test were performed (using two 2200-Fans with DM-2A manometers, Retrotec Energy Innovations Ltd.), using a fan-screen placed in a smaller outer doorway. In one case, the crawl space apertures were sealed but remained opened in the other. Results indicate that the floor of the church is leaky. The air change rate (ACH), was measured by the tracer gas decay method, see e.g. ISO 12569 (CEN-European Committee for Standardization, 2012), with SF_6 as tracer gas. The room air inside the church found to be quite well-mixed especially when the churches were heated. More details on these tracer gas measurements can be found in (Mattsson et al., 2011), which reported remarkably good air mixing at repeated measurements in three different churches. Air change rate was measured at three different occasions (in May, June and October), totally covering a time period of about 90 hours.

Numerical model

In general, the numerical one zone model constitutes a cuboid on top of a crawlspace, separated by a leaky intermediate floor. The crawlspace is handled as a zone without buoyancy, since the air in the space is assumed to have the same temperature as the outdoor air. Irregularities of the ceiling of the great hall are handled by using the volume weighted averaged ceiling height to attain the correct magnitude of the buoyancy forces. Walls are considered airtight. Leakages are identified and entered in the model where the flow due to each leakage is calculated. Actually, the total pressure difference caused by fans, wind or/and buoyancy is calculated as a function of NPL. Then by solving the continuity equation for the total flow, the NPL is gained resulting in the flow due to each leakage. The model works iteratively in finding NPL at each façade, where the criterion is that the sum of all in- and exfiltrating air of the zones is zero. In case of wind, pressure coefficients at the facades have assessed in wind tunnel experiments, see e.g. (Mattsson et al., 2013).

Observations of leakage sources in the great hall (assessed by audit and IR-thermography during pressurization) are categorized as vertical or horizontal gaps (i.e. cracks or joints between building components) or as holes (apertures with a circular geometry). The locations, especially in height and orientation, are listed in the model. The categorization is based on many assumptions, such as the width, length and depth of gaps and geometry behind the visible leakages. The depths of apertures are assumed to have the same thickness as the construction or joints of construction components. The apertures in the crawlspace are treated as large orifices, since these measure 30x30 cm². These apertures are equipped with perforated grids, which are currently neglected but will in future work be implemented.

In the model, Poiseuille's equation is used for the air leakage paths considering both laminar and turbulent flow (White, 2011). The main equation is:

$$\Delta P = \left(\xi + \lambda_f \frac{b}{D_h}\right)\rho \frac{u_m^2}{2} \qquad (2)$$

where ΔP is the pressure difference over the leakage path (Pa), ξ is the entry and exit loss term (normally set as 1.5), b is the thickness of the construction (m), ϱ is the air density, i.e. 1.2 kg/m³, u_m is the mean air velocity in the aperture (m/s) and D_h is the hydraulic diameter (m) and is equal to two times the width (e.g. a narrow crack) or the diameter (circular hole) of the leakage. λ_f is the Poiseuille flow friction factor, representing the laminar part of the flow, and it depends on the shape of the leakage path and is set to $64/Re$ for circular aperture and $96/Re$ for rectangular ones. Re is the Reynolds number. (White, 2011)

Initial data from the field audit (leakage position and characteristics), were categorized as rectangular gaps or circular openings; see Table 2 for categorization types. This data was entered in the program, with the intention of obtaining simulated values that correspond to measured power law equations from blower door test; normally, involving discrepancies. Looking at graphical plots (log-log of pressure difference versus flow rate), there are two types of discrepancies for the simulated and measured curves: flow rate magnitude and flow exponent (the latter in terms of curve tilt). Flow rate values may be increased by increasing aperture area (D_h or width of a crack) if the location and depth is fixed (as mentioned previously, b is the thickness of the construction). Changes in width will only increase or lower the flow quantity through a gap, without influencing the flow exponent. However, a change in D_h will affect the exponent; reducing D_h will increase the exponent whilst reducing flow and, vice-versa, increasing D_h will for the same pressure difference allow more flow but reduce the flow exponent. The aperture area of each leakage category can be adjusted since these are difficult to assess - we call this a type of "calibration" of the model. Due to blower door's unidirectional flow, the aperture sizes may be fitted for pressurized conditions but be distributed erroneously. To further improve the calibration, a measured NPL during non-windy condition was simultaneously used. NPL is sensitive to aperture size and location; it is generally in the vicinity where the number and size of apertures is greatest. NPL situated at a low height indicates concentrated infiltration in lower parts of the building.

Two blower door cases were used (one where apertures of the crawlspace were open and the other where these were sealed) and the other case with natural conditions, where the measured NPL (namely ~ 3.8 m), as presented in

(Mattsson et al., 2013). In order to improve correspondence between simulated and measured results, gap hydraulic diameters and lengths were varied in multiple runs. These variations ("calibrating" input data to improve accuracy) were not performed in a systematic way; these were made on basis of trial and error with guidance of flow characteristics as described above. Table 2 shows final input data.

Table 2. Leakage characteristics

Envelope component	Description	Amount	Height (m)	Length (m)	Thickness/ depth (m)	Width/ radius (m)	Low position (m)
Southern wall	Gap around door	2	2.9	1.70	0.10	0.006	0.0
	Circular opening	1			0.10	0.005	1.5
Western wall	Gap around door	1	2.9	1.7	0.10	0.006	0.0
	Gap around window	12	4.7	1.0	0.10	0.001	2.0
	Circular opening	1			0.10	0.005	1.5
Northern wall	Gap around window	12	4.7	1.0	0.10	0.001	2.0
Eastern wall	Gap around door	1	2.9	1.7	0.10	0.006	0.0
	Gap around window	12	4.7	1.0	0.10	0.001	2.0
	Circular opening	1			0.10	0.005	1.5
Ceiling	Horizontal gaps	2		65.0	0.15	0.003	11.0
	Circular opening	15			0.15	0.0075	11.0
Floor	Horizontal gaps	1		220.0	0.045	0.002	0.0

RESULTS AND DISCUSSION

Input data of Table 2 rendered simulated blower door results as displayed in Fig. 2, together with measurement results. Flow exponents for the model are higher than the ones gained from Blower door measurements. One reason is that the modelled theoretical gaps and leakages are smooth and straight. But in reality, leakage gaps are not perfectly shaped which make the passing flow more turbulent. Thus the measured flow by blower door is more turbulent and has a flow exponent closer to 0.5, i.e. full turbulent flow. But there are more explanations as follows.

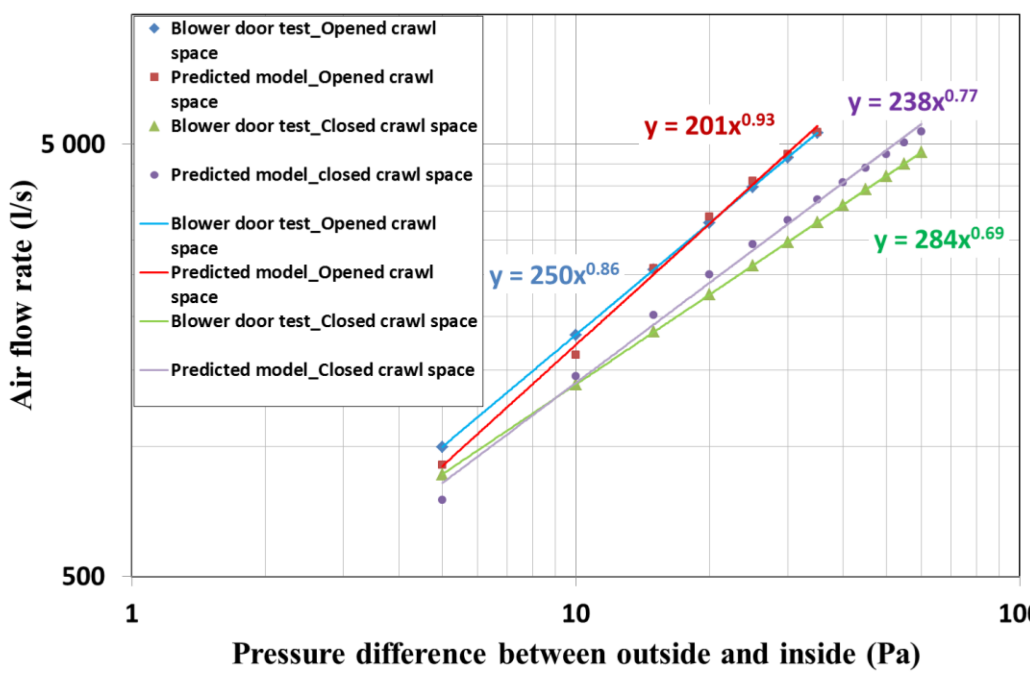

Figure 2 Blower door results for two cases: the apertures of the crawlspace are opened or closed. Power law relationship between pressure difference (x) and airflow rate (y) are presented for each case.

The total area of the model's leakage apertures in the main zone sum up to be 1.15 m², where 28 %, 34 % and 38 % are distributed on walls, ceiling and floor, respectively. However, test results indicate that ELA@4Pa is 0.32 m². The discrepancy in areas is due to the nature of Poiseuille´s equation, which has a linear pressure loss within the gap/hole and the non-linear entry and exit loss term. ELA is defined on basis of entry and exit pressure loss in an orifice plate and does not contain a linear pressure loss term. Therefore, for a specific pressure difference and airflow, ELA will be smaller than that calculated with Poiseuille's equation. In turn, this also affects the flow exponent. If the linear pressure loss is much larger than the entry and exit pressure loss, then the flow exponent has a value close to 1. If the gap depth is reduced, the entry and exit loss term becomes more dominant, giving a flow exponent that is closer to 0.5. A reduction in gap depth will result in larger flows, which in Figure 2 is over-estimated for the case where crawlspace apertures are closed (keeping in mind that gap depths are in this model fixed construction thickness).

Apart from blower door data, NPL at natural conditions is used in the calibration. Simulated NPL was compared with the measured one by primarily adjusting the length, thus aperture area, of each leakage path. The measured NPL was ~ 3.8 m and the simulated NPL ~ 3.6 m. Since NPL is very sensitive to leakage distribution, especially in height, it is an important variable to use in calibration.

Having performed the "calibration" above, model input was changed to data that was monitored during two days of natural conditions. Figure 3 illustrates the correspondence between measured and simulated (predicted) results. The results are scattered around the "Predicted=Measured" line with a coefficient of determination (R^2-value) of 0.61. This result is in parity with results from LBL and AIM-2 models tested for this church, by Hayati et al. (2014), though those results were consistently scattered above the "Predicted=Measured" line, generally over-predicting air infiltration. The result presented here illustrates the reliability of the numerical model and shows fair agreement with the other semi-empirical models like LBL and AIM-2. The presented model is being developed and it is expected to have better results since it is based on physically correct assumptions. More evaluations with greater variation in weather data are required to get a full picture of the model reliability.

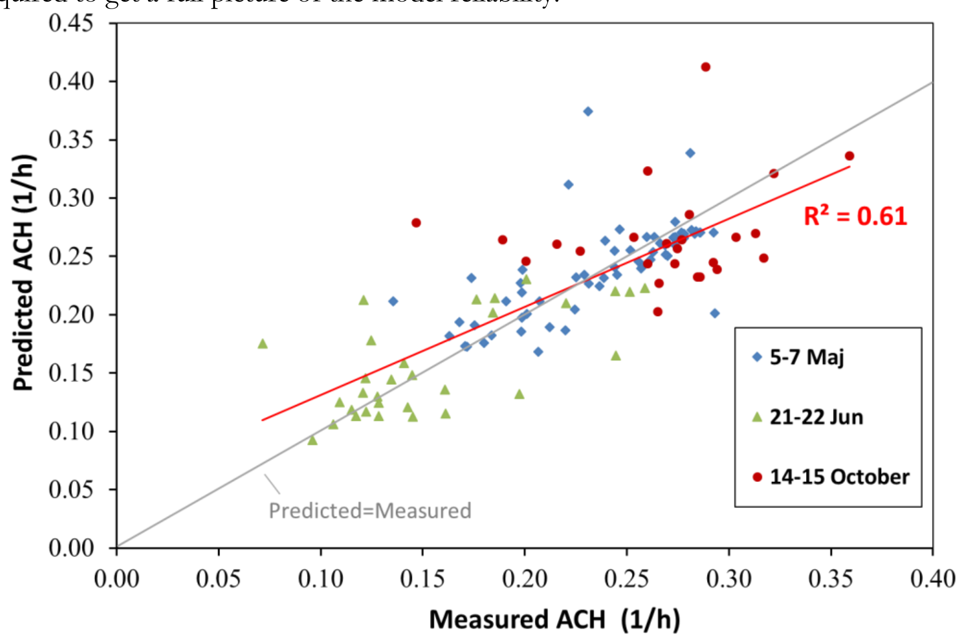

Figure 3 Predicted (simulated) and measured infiltration rates during 5-7 May, 21-22 June and 14-15 October.

CONCLUSION

A numerical model to calculate air leakage in natural conditions is being developed. The model is based on physical relationships where leakage paths are represented by Poiseuille's equations. Blower door data and a measurement of NPL are required, as well as leakage characteristics assessed at site, for example by audits and IR-thermography. The total pressure difference caused by fans, wind or/and buoyancy is calculated as a function of

NPL. The total flow rate, i.e. summation of the all in-outflows due to each leakage path, is solved iteratively. A crucial part of the program is the calibration of leakage characteristics, much owing to practical difficulties in assessing these. The calibration consists of adjusting leakage areas (hydraulic diameters and gap lengths) so that simulated blower door curves and NPL in natural condition agreed with corresponding measured entities. In this case, aperture locations in the zone and depths have been fixed. This calibration has been performed manually (trial and error) and will in the future be done systematically to improve accuracy furthermore.

This model is applied in the case of a church that can be considered as one zone on a crawlspace. The final sets of gaps/holes and the distribution gave adequate simulated blower door results that have somewhat higher slopes (flow exponents) than those measured. The calibration procedure also included a natural condition case, where the simulated NPL was compared with the measured NPL, since NPL is dependent on location and size of leakages. Model results were compared with measured ACH in natural conditions at three different occasions (in May, June and October), totally covering a time period of about 90 hours. The R^2-value is 0.61, which is in the same order of magnitude as those obtained from LBL and AIM-2 model applied on the same building. This validates the functionality of the numerical model; however, further evaluation of the reliability of the model is being studied with greater variation in weather data and buildings. This model has potential of being promising in this application (stone churches) and other types of buildings if a systematic calibration procedure can be developed in the future.

The challenging part in building air tightness context is to couple the blower door results with what happens in natural condition. Blower door is set as standard, (EN13829, 2000), and is widely used for building tightness purposes and building related regulations; however, test pressurization is far beyond the natural conditions. This study is an effort to make this coupling by field investigation based on physical assumptions closer to the real scenario; to improve simulation accuracy in comparison to existing models. Tracer gas measurements are quite cumbersome while blower door method is more practicable and the point of this study is to make a stronger connection with natural condition and make it more practically and physically correct.

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REFERENCES

CEN-European Committee for Standardization. (2012), "ISO12569, Thermal performance of buildings and materials -- Determination of specific airflow rate in buildings -- Tracer gas dilution method. ISO Standard 12569:2012."

ASHRAE, (2013), ASHRAE Handbook Fundamentals, "Chapter 16. Ventilation and Infiltration" American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA

Dufour, M.B., Derome, D. and Zmeureanu, R. (2009), "Analysis of thermograms for the estimation of dimensions of cracks in building envelope", Infrared Physics & Technology, Elsevier, Vol. 52 No. 2, pp. 70–78.

EN13829. (2000), "Thermal insulation - Determination of building air tightness - Fan pressurization method. European standard, CEN, Brussels."

Etheridge, D. (2011), Natural Ventilation of Buildings: Theory, Measurement and Design, Wiley.

Hayati, A., Mattsson, M. and Sandberg, M. (2014), "Evaluation of the LBL and AIM-2 air infiltration models on large single zones: Three historical churches", Building and Environment, Elsevier Ltd, Vol. 81 No. 0, pp. 365–379.

Mattsson, M., Lindström, S., Linden, E. and Sandberg, M. (2011), "Tracer Gas Techniques for Quantifying the Air Change Rate in Churches–Field Investigation Experiences", in Proc. Roomvent 2011: 12th International Conference on Air Distribution in Rooms., Mathisen, H.M. (Ed.), ISBN: 978-82-519-2812-0, Paper No 235, Trondheim, Norway.

Mattsson, M., Sandberg, M., Claesson, L., Lindström, S. and Hayati, A. (2013), "Fan pressurization method for measuring air leakage in churches–wind and stack induced uncertainties", Conference Proceedings: Cultural Heritage preservation–3rd European Workshop on Cultural Heritage Preservation, pp. 63–68.

Sherman, M.H. & Grimsrud, D.T., 1980. Measurement of Infiltration Using Fan Pressurization and Weather Data. In Proceedings. Air Infiltration Centre, p. 277.

Sherman, M.H. (1992), “Superposition in infiltration modeling”, Indoor Air, Vol. 2 No. 2, pp. 101–114.
Walker, I.S. & Wilson, D.J., 1990. AIM 2: The Alberta air infiltration model. University of Alberta, Department of Mechanical Engineering Report 71.
Walker, I.S. and Wilson, D.J. (1993), “Evaluating models for superposition of wind and stack effect in air infiltration”, Building and Environment, Vol. 28 No. 2, pp. 201–210.
White, F.M. (2011), “Fluid mechanics. (7thedn)”, McGraw Hill, New York.