Uncertainty of climate related parameters of a building envelope – case of leakage characteristics

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SUMMARY:

Airflow through the building envelope depends on the airtightness of the structure specified by the type of construction and the quality of the workmanship. If we neglect the latter reason, the actual airtightness performance of the building depends on the regime of the airflow through the openings which is a combination of laminar and turbulent ones. The leakage characteristics of a building vary according to the changes of the regime of the flow with the pressure difference across the building envelope. The leakage characteristics are presented by a dimensionless discharge coefficient that relates the flow rate through the openings to the area of building components and the corresponding pressure difference across the openings. It is proposed to treat the discharge coefficient as a variable, which could be estimated from the blower door tests. The results of pressurization and depressurization tests carried out on the single-family house using reductive sealing method related to the different parts of the structure are presented. The uncertainties coupled to the regime of the airflow are reflected by the variation of dimensionless discharge coefficient which in terms of probability density function could be applied in the reliability models of, for example, air exchange performance of buildings.

1. Introduction

This study is in line with the research area being developed during 2010 to 2013, under the custody of Annex 55 within IEA-EXCO "Reliability of Energy Efficient Building Retrofitting – Probability Assessment of Performance and Cost (RAP-RETRO)". The paper relates to the concept and program of measurements described in (Pietrzyk 2000).

Reliability of a design considers the stochastic variability of different sort of data that could be divided in to 3 groups (Pietrzyk 2005a). The first group consists of the load data treated as random variables, which can be described by the typical, for the site or the living style, family of distributions. The second group consists of the parameters, which variations oscillate around the mean value. The example of such parameter can be a material property randomly varying in space due to uneven quality of the product. This group contains also the coefficients, which values are uncertain or inaccurate stated, and as a consequence, a certain interval of that value has to be taken into account. The third group of random variables is formed by load related data describing the properties of a construction, which are load dependent, like for example thermal transmittance (especially dynamic U-value), or leakage characteristic. The important research task is to find the probabilistic regularities typical for the climate-construction interaction (Pietrzyk & Hagentoft 2004).

Leakage characteristics of the building envelope are treated as climate related parameters of construction and presented in this study in terms of dimensionless discharge coefficient.

2. Airflow through a building envelope

Airflow through a building envelope is a combination of laminar and turbulent flows.
It depends on the type of construction and conforms to a relationship expressed by the Power Law Equation (Etheridge & Sandberg 1996):

$$Q = k(\Delta p)^{n_k} \tag{1}$$

Where

- Q - airflow rate (m^3/h)
- k - flow coefficient depending on the total size of all the leakage passages $(m^3/h/Pa^{n_k})$
- Δp - pressure difference across building envelope (Pa)
- n_k - flow exponent varying between 0.5 for turbulent flow and 1.0 for laminar flow

The flow coefficient and flow exponent are usually assumed to be constant and can be estimated from the results of blower door tests.

Air leakage through the building envelope depends on the applied pressure difference. It is important to know the relationship between airflow and pressure difference since it is unique for every house. It can be estimated from the leakage values assumed for adventitious and purpose provided openings. This relationship can also be measured by means of blower door tests. Sometimes, instead of Equation 1, it is more convenient to use a different form for the relationship between the flow and pressure difference which is based on the fixed power $n_k = 0.5$ (as for orifice flow). A flow coefficient varies with Δp depending on the changes of real regime of the flow and the leakage characteristics of the openings. Assuming a mostly turbulent regime of the flow through the openings we arrive at the following equation describing the flow Q (Wirén 1985):

$$Q = IA\sqrt{\frac{2\,|\Delta p|}{\rho}} \tag{2}$$

Where

- Q - airflow (m^3/s),
- Δp - pressure difference across a building envelope (Pa),
- A - area of building envelope (m^2),
- ρ - density of air (kg/m^3)
- I - dimensionless discharge coefficient characterising leakage properties of the building, relating the flow rate through the openings to the area of building component and the corresponding pressure drop across openings (-).

$$I = f(Re)\,\alpha \tag{3}$$

$$\alpha = \frac{A_1}{A} \tag{4}$$

- α - relative leakage area (-)
- A_1 - area of leakage openings (m^2)
- f(Re)- coefficient dependent on Reynolds number and including the effect of frictional characteristic of the openings, cracks and leaks (-)

The coefficient I can be presented as a linear function of "frictionless flow velocity" through the openings v_q, which in turn depends on the pressure difference.

$$I = a\,v_q + b \tag{5}$$

Where

- a - parameter of linear regression $I(v_q)$ (s/m)
- b - parameter of linear regression $I(v_q)$ (-)

$$v_q = \sqrt{\frac{2\,|\Delta p|}{\rho}} \tag{6}$$

In the case of big openings, the flow is turbulent and the leakage parameter can be considered to be constant (the minor losses are independent of the Reynolds number). For the other openings, where a boundary flow occurs, leakage properties can vary significantly with the magnitude of pressure difference (Wirén 1985). The changes of Reynolds number with an increase of flow velocity induced by larger pressure differences make the parameters I and K dependent on Δp.

Evaluation of the parameters of the regression $I(v_q)$ is possible using the results of blower door test. Examples of the function $I(v_q)$, evaluated for the experimental house, for a turbulent flow through the opening and boundary flow through the walls are presented in the following section.

3. Experiment

The experimental building is a two-storey timber-framed single family detached house with a concrete basement. A garage with doors facing south is located in the extended south part of the cellar. Figure 1 shows photographic view of the Southern side of the building together with the drawing of the façade. The external walls as well as the roof are insulated with a 0.265 m layer of mineral wool. A plastic sheet is mounted inside the insulation to provide good air-tightness. The external face of the wall is timber clad with an air cavity behind it.

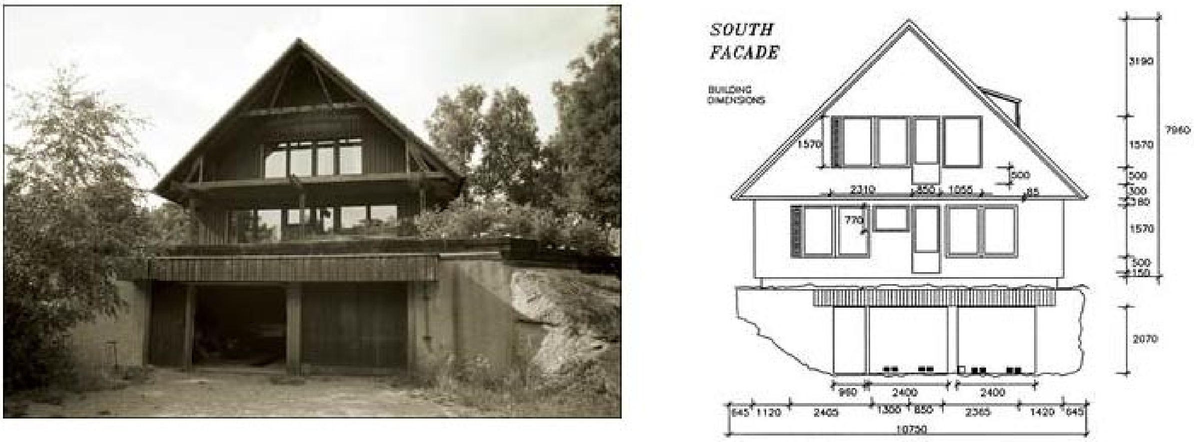

Figure 1. The Southern façade of the experimental building

The leakage characteristics of the building were evaluated using blower door tests. In the case when discharge coefficient I is evaluated for the whole building, big openings should be treated separately in the model with own leakage characteristics. Location of the leakage associated with the opening can be identify by means of thermograph and measured by reductive sealing method.

3.1 Air-tightness of the building

According to the Code of Practice (Boverkets Byggregler 1994) air tightness of a building is characterised by the average air leakage through the part of the building forming the boundary with outdoor air or an unheated space, and measured at a pressure difference of 50 Pa. An estimation of the total leakage at a pressure difference of 50 Pa Q(50) was done by means of pressurisation and depressurisation tests according to the Swedish Standard (SS 021551, 1987). The measurements were carried out in 1991 and the instrumentation used is described in (Schechinger & Handa 1993).

Investigations of the air tightness of the building have been made in different conditions according to the different area of intentional openings existing in the envelope: the outlet of ventilation system, the passage to the attic, the ventilation windows, the door for the cat and the opening under the garage door situated in the cellar.

The configurations of the openings measured by blower door tests that were eventually used to estimate discharge coefficients for the whole building and for the big opening under the garage door are listed in Table 1.

Table 1. Configuration of the openings during the blower door tests

	Case no.	Ventilation duct	Attic	Ventilation window	Cat door	Opening under the garage door
Whole build.	2	Not sealed	closed	closed	sealed	Not sealed
	6	Not sealed	closed	closed	sealed	sealed
Cellar	11	The floor between the cellar and the living part of the house is sealed			sealed	Not sealed
	12				Not sealed	Not sealed
	13				Not sealed	sealed

The results are presented in terms of parameters of the power law equation (Equation 1) in Table 2. The table contains the flow coefficients and the flow exponents estimated for different cases from the results of pressurisation and depressurisation tests. The root-mean-square error, evaluated for each set of parameters fitted, is found to be proportional to the magnitude of airflow through the building envelope.

Table 2. Parameters of the leakage curves fitted to pressurisation and depressurisation data for different cases.

Case no.	Pressurisation test $Q = k\Delta p^n$			Depressurisation test $Q = k\Delta p^n$		
	k	n	rms error	k	n	rms error
2	214.2	0.67	25.4	190.2	0.67	15.4
6	95.7	0.69	6.7	80.3	0.72	7.3
11	225.8	0.64	27.5	219.9	0.62	25.2
12	229.7	0.66	22.3	240.2	0.62	35.6
13	94.2	0.73	12.2	106.0	0.69	14.3

The example of fitting of leakage curves for pressurisation and depressurisation data for cases 11, 12 and 13 described above are presented in Figure 2.

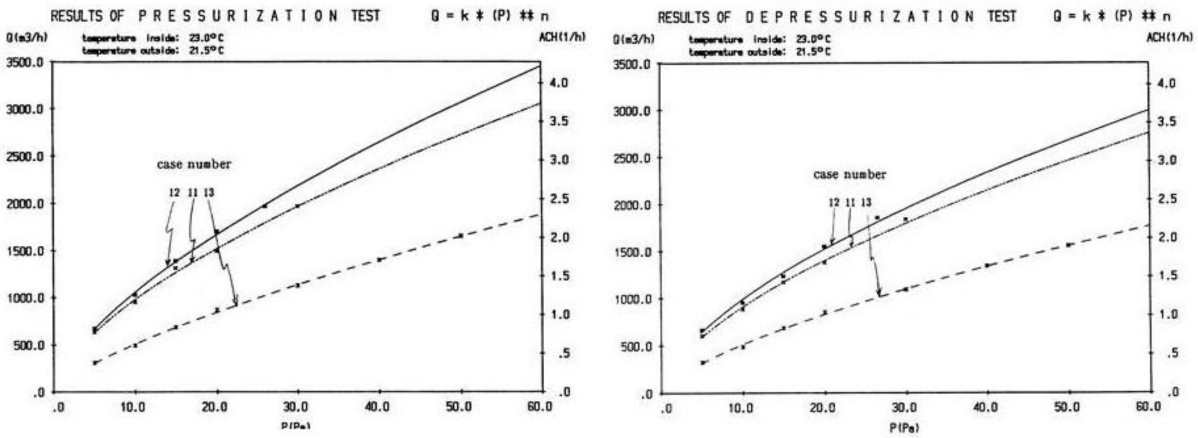

Figure 2. Results of the blower door tests for the cases: 11, 12, 13 (Table 1)

The analysis of the results from Table 2 exemplified by Figure 2 gives an idea of the possible influence of the above-mentioned openings on the air tightness of the building. Generally, from the all cases measured (Pietrzyk 2000) (1-14 that are not listed here) it was realised that: the outlet of the ventilation duct in the range of 0 to 30 Pa, which is particularly interesting for our study, seems to be less important; the passage to the attic hardly has any influence on the exchanged air due to the fact that the insulation is not put in the attic floor but directly under the roof; the ventilation windows could have a significant influence on the air tightness of the building but they were usually closed.

The opening under the garage door has the greatest influence (compare cases no. 11 and 13). At a pressure difference of 10 Pa it causes approximately 0.5/hour ACH whereas the pressure difference of 30 Pa increases this value to 1./hour. At 50 Pa ACH caused by this opening reaches a value of 1.2/hour which is about 40% of the air change rate caused by all of the openings existing in the building envelope. The cat door situated in the garage door at the ground level contributed significantly less to the amount of air being exchanged. It was more important at pressure differences less than -15 Pa (see cases no.11 and no.12 for pressurisation tests). The cat door and the big opening under the garage door could be treated as one opening in the model for air change rate.

The results of the measurements for cases no. 11, no. 12 and no. 13 show that investigated openings in the cellar work more efficiently to transport air into the house than out of the house (the flow exponent estimated for the pressurisation test is greater than the flow exponent from the depressurisation test).

Cases no. 12 and no. 13 have been measured with a fan situated in the cellar, with the floor between the cellar and the upper part of the building sealed. In that way the influence of cracks in the living area was limited. A subtraction of the results of case no. 13 from the results of case no. 12 also cancels the effect of openings in the garage room. The configuration of the openings in the case no. 2 is close to ordinary serviceability conditions during the measurement period. Case no. 6 characterises the air tightness of the building under the same conditions but with the influence of the near-to-ground opening under the garage door and the cat door excluded. Cases no. 6 and case no. 12 minus no. 13 are complementary and together fully describe the air tightness of the house during the measurement period.

3.2 Discharge coefficient – deterministic evaluation

The airflow through the envelope (Equation 2) can be presented in the following form (Wirén 1985):

$$Q = K\ A\ \sqrt{|\Delta p|} \qquad (7)$$

Where $$K = I\sqrt{\frac{2}{\rho}} \qquad (8)$$

K - leakage function [$\sqrt{m^3/kg}$]

Similarly to discharge coefficient I (Equation 5), a leakage function K is also presented as a linear function of v_q:

$$K = a_K v_q + b_K \qquad (9)$$

Cases no. 2 and no. 6 describe the air tightness of the whole building with a certain configuration of openings while case no.12 minus no.13 is characteristic only for the opening under the garage door together with the cat door.

The example of detailed results of the evaluation of the parameters like flow through the openings, air change rate, I and k coefficients for different pressure differences and estimation of the functions of $K(v_q)$ is shown in Table 3 for the pressurisation test for case 6. The definitions of the symbols are:

p - pressure difference applied in the building during the test (Pa)
fl - pressure difference measured as a result of test (Pa)
q - flow through the openings (m^3/h)
Q - flow through the openings corrected due to the difference of temperature of the air outside T_{ext} and inside T_{int} the building (m^3/h) or (m^3/s)
rms - rms error of approximation
I - dimensionless discharge coefficient (-)
K - leakage function [$\sqrt{m^3/kg}$]
k - flow coefficient depending on the total size of all the leakage passages $(m^3/h/Pa^{n_k})$

Table 3. Detailed results of pressurisation test - case no. 6.

The results of p r e s s u r i s a t i o n test case 6
for a house with A= 413.0 m2 and V= 819.0 m3
Tint = 23.5 Text = 21.0

p(Pa)	fl(Pa)	q(m3/h)	Q(m3/h)	k	ACH(1/h)
5.0000	3.0000	285.2710	287.6955	128.6613	.3513
10.0000	8.0000	462.2045	466.1328	147.4041	.5691
15.0000	14.0000	608.7079	613.8813	158.5035	.7495
20.0000	21.0000	743.0975	749.4131	167.5739	.9150
30.0000	36.0000	968.7568	976.9902	178.3732	1.1929
40.0000	56.0000	1203.9890	1214.2220	191.9853	1.4826
50.0000	74.0000	1380.9440	1392.6800	196.9547	1.7005

k = 180.73370 n = .50000 rms = 87.77390
Q(50.)=1278.0 m3/h

p(Pa)	fl(Pa)	v_q(m/s)	Q(m3/s)	K	I
5.0000	3.0000	2.8859	.0799	.00008654	.00006705
10.0000	8.0000	4.0813	.1295	.00009914	.00007682
15.0000	14.000	4.9986	.1705	.00010661	.00008260
20.0000	21.000	5.7718	.2082	.00011271	.00008733
30.0000	36.000	7.0690	.2714	.00011997	.00009296
40.0000	56.000	8.1626	.3373	.00012913	.00010005
50.0000	74.000	9.1261	.3869	.00013247	.00010264

K = .00012156 n = .50000 rms = .0243816

$K = .00000728 * v_q + .00006856$

The estimated function $I(v_q)$ for these cases are presented in Figure 3. The parameters of these relationships are shown in Table 4, together with the flow exponents evaluated from Equation 1.

Table 4. Parameters of relationship $I = a_I v_q + b_I$ and the flow exponent related to the case.

case no.	parameter a_I * 10^{-4}	parameter b_I * 10^{-4}	flow exponent
2	0.1247	1.0247	0.668
6	0.0570	0.5300	0.686
12-13	0.0095	0.7354	0.530

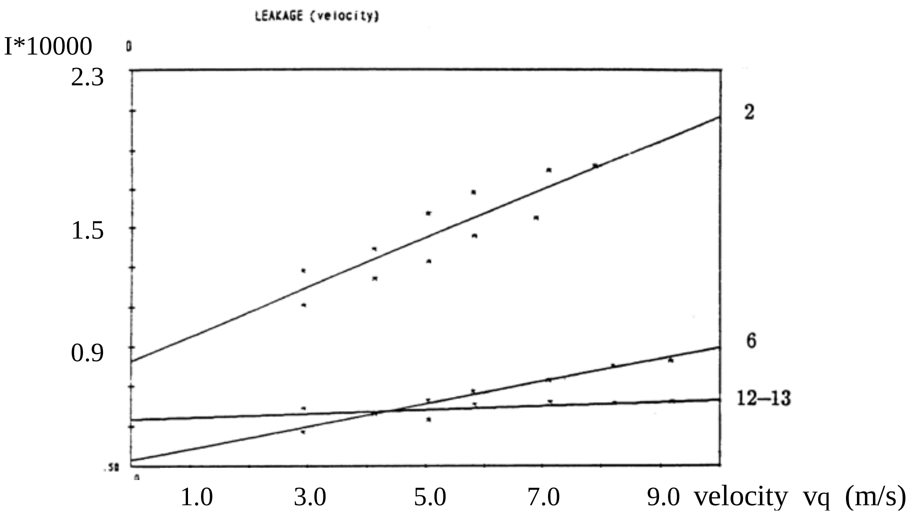

Figure 3. The function $I(v_q)$ estimated for different cases: 12-13 - when turbulent flow occurs 2, 6 - when boundary flow occurs

The flow through the opening under the garage door (see case no. 12 minus case no. 13) seems to be turbulent according to the value of the flow exponent (see Table 4). The line describing the relationship $I(v_q)$ related to this case presented in Figure 3 is almost horizontal because for fully turbulent flow minor losses are constant and do not depend on Reynolds number.

3.3 Discharge coefficient – stochastic representation

Discharge coefficient can be evaluated for specified periods of time using design parameters of the house together with climatic characteristics of the site: local wind speed for specified wind directions and outdoor temperature. Probability density function of I has been approximated using FORM (First-Order Reliability Method) where the wind and buoyancy driven pressure drop was a function of two random variables: the wind speed given wind direction sector and the temperature difference across the building envelope. Both variables have been represented by statistical parameters of probability density functions for one-hour mean data. The procedure is described in (Pietrzyk 2000, Pietrzyk & Hagentoft 2008a,b). The probabilistic description of discharge coefficient I described by Equations 5 and 6 is illustrated in Figure 4. It relates to the case 6 (see Tables 3 and 4).

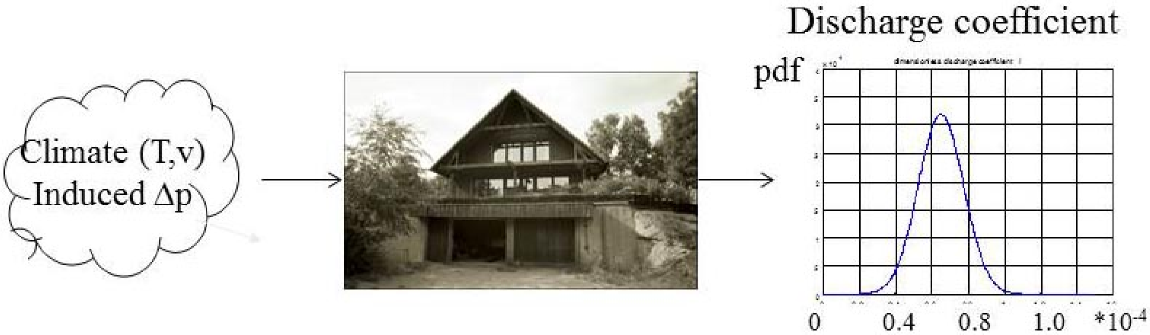

Figure 4. Probabilistic model of discharge coefficient of a building envelope.

The flow through the opening under the garage door (together with cat door) is close to turbulent. Coefficient *I* does not seem to be dependent on the pressure drop (see case 12-13 in Figure 3), and neither does the leakage parameter *K*. Due to this fact, a fully turbulent flow through that opening has been assumed in the model. A flow exponent of 0.5 and a constant value of the discharge coefficient *I* have been assigned to describe flow through this opening.

4. Conclusions

Dimensionless discharge coefficient is represented by a unique function for the building component or for the whole building envelope. Its variation reflects the microclimatic impact of the environment on air-tightness performance.

Dimensionless discharge coefficient could be treated as a climate dependent parameter of the building defined by the probability density function. The leakage characteristics of a building vary with the pressure difference across the building envelope according to the changes of real regime of the flow (laminar, turbulent) through the openings. Dimensionless discharge coefficient relates the flow rate through the openings to the area of building components and the corresponding pressure difference across the openings.

The dimensionless discharge coefficient *I* in the form of regression coefficients *a* and *b* could be used as the input data to the reliability model: Parameters *a* and *b* of Equation 5 can be evaluated from the results of blower door tests carried out on the standard components or they can be assumed according to design values of the leakage area. In the case when leakage characteristics are evaluated only for the whole house the dimensionless discharge coefficient should be estimated also for a dominant opening, if it exists.

The application of the dimensionless discharge coefficient in the probabilistic model of air infiltration in a building is described in (Pietrzyk 2000, 2005b and Pietrzyk & Hagentoft 2008b).

5. Acknowledgments

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