Probabilistic model PROMO for evaluation of air change rate distribution

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ABSTRACT: The probabilistic model (PROMO) applied to the problem of air infiltration in low-rise buildings is presented. The PROMO model allows the estimation of the effect of variations of climatic conditions on air exchange in a building. In PROMO, experimental data are used in order to evaluate the parameters and types of the distributions of temperature, wind speed, and wind direction. Those distributions are employed to evaluate the distributions of air change rate caused by air infiltration and can be used to estimate probability of inadequate ventilation. FORM (First-Order Reliability Method) technique is used for probabilistic approximations. For validation of the PROMO model, the probability density functions of the air change rate for the test house situated near Gothenburg are estimated from the results of full-scale measurements of pressure differences across the envelope and compared to those calculated by PROMO from the climatic parameters measured at the site. The agreement of the results obtained in these two ways is very good.

KEYWORDS: air infiltration, air change rate, probabilistic model, reliability, FORM

INTRODUCTION

The main subject of the paper is a study of climate-induced air infiltration in low-rise buildings. The probabilistic model PROMO, allowing the estimation of probability density functions of air change rate has been developed and validated with the help of experimental data. It can be used to evaluate the contribution of air infiltration to ventilation and energy balance and the influence of that contribution on the reliability of air exchange or reliability of energy performance of a building. In the context of air exchange, air infiltration constitutes a complement to the design of ventilation. This complement is often disregarded, or considered in a very simplified manner. The tendency of relying to larger degree on natural ventilation calls for better modelling techniques for air infiltration. An attempt to create such a modelling technique is presented. A modelling approach proposed seems very well suited to handling the natural driving forces governing the rate of air infiltration. It also gives a possibility to quantify the probability of insufficient or excessive air exchange (Pietrzyk, 2000).

Physical relationships for air infiltration and ventilation in buildings, which form the background to the probabilistic modelling can be found in the AIVC publications (for ex. in Liddament, 1986), or in (Etheridge & Sandberg, 1996). FORM technique is used for the probabilistic approximations of air change rate (Pietrzyk & Hagentoft, b, Pietrzyk 2000) and reliability analysis (Pietrzyk, 2000, c). The description of FORM can be found in (Haldar, 2000, Ditlevsen, 1996) and also in (Pietrzyk & Hagentoft, a).

PROBABILISTIC MODEL PROMO

The probabilistic model PROMO has been created under the following assumptions: a low-rise building with single ventilation and temperature zone, the steady-state conditions of air flow, the leakage area uniformly distributed over a building component except for the big openings. The detailed description of the model can be found in (Pietrzyk & Hagentoft, b).

Input data to the infiltration model

The input data to the infiltration model consist of random variables (italic bold text) and deterministic parameters. The probability density functions of random variables are estimated from the series of hourly experimental data. The family of distributions, typical for certain climatic parameters can be chosen.

1. Environmental data (description of the site and climatic data):

wind speed and ***wind direction*** from the nearest meteorological station (the set of measurements or parameters of the statistical distributions) for each wind direction sector d: surface roughness, the evaluation of the sheltering effect of the nearest surrounding, ***external temperature*** (the set of measurements or parameters of the statistical distribution), correlation coefficient between wind speed and external temperature

2. Parameters of a building:

geometry of the building (the area of building components A_j, the volume of the house V, etc.), the leakage characteristics of the house estimated for each building component and/or for the whole building, the location of neutral pressure layer, the orientation of the building against different wind directions, the pressure coefficients Cp_{ext} and Cp_{int} for different facades and wind direction sectors accounting for the sheltering effect of the surroundings

3. Serviceability data:

assumed ***internal temperature*** during heating season, intentional openings

Infiltration model

The infiltration model given by Equation 1 is based on the superposition of wind and stack effect (Etherige,1996). Temperature difference across envelope, and wind speed v evaluated for each direction sector d are treated as random variables.

$$ACH_d = \sqrt{s_1 \Delta T^2 + s_2 |\Delta T| + s_3 |\Delta T|^{1.5} + w_{d,1} v_d{}^4 + w_{d,2} v_d{}^2 + w_{d,3} v_d{}^3} \qquad (1)$$

where s_1, s_2, s_3 are deterministic coefficients dependent on the parameters of the flow balance for the stack effect, $w_{d,1}$, $w_{d,2}$, $w_{d,3}$ are deterministic coefficients dependent on the flow balance for various wind directions d.

$$s_1 = \left(\frac{3600}{V}\right)^2 \left(0.044\frac{2}{\rho}\right)^2 \left(\sum_{j=1}^{n} A_j a_j |z_j|\right)^2$$

$$s_2 = \left(\frac{3600}{V}\right)^2 0.044\frac{2}{\rho} \left(\sum_{j=1}^{n} A_j b_j \sqrt{|z_j|}\right)^2$$

$$s_3 = 2\left(\frac{3600}{V}\right)^2 \left(0.044\frac{2}{\rho}\right)^{1.5} \left(\sum_{j=1}^{n} A_j a_j |z_j|\right)\left(\sum_{j=1}^{n} A_j b_j \sqrt{|z_j|}\right)$$

$$w_{d,1} = \left(\frac{3600}{V}\right)^2 \left(\sum_{j=1}^{n} A_j a_j \left|C_{p,d,j}\right|\right)^2$$

$$w_{d,2} = \left(\frac{3600}{V}\right)^2 \left(\sum_{j=1}^{n} A_j b_j \sqrt{\left|C_{p,d,j}\right|}\right)^2$$

$$w_{d,3} = 2\left(\frac{3600}{V}\right)^2 \left(\sum_{j=1}^{n} A_j a_j \left|C_{p,d,j}\right|\right)\left(\sum_{j=1}^{n} A_j b_j \sqrt{\left|C_{p,d,j}\right|}\right)$$

The coefficients a_j and b_j describe leakage characteristics of the building component j. They 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. Parameter z_j gives the location of the component related to the neutral pressure layer.
The probabilistic distributions of the air change rate are approximated using FORM. The air change rate follows different probability distributions depending on the contribution and the quantity of the stack and wind forces as well as leakage distribution over the envelope.

CASE STUDY

Description of the test house

The object of the study is a two-story timber-framed one family detached house with a concrete basement situated near Gothenburg. There is an open passage between the basement and the living area. The house is surrounded by a forest with trees of different heights excluding the southern side of a building exposed to an open area. The house was constructed in 1979 with the intention of using it for experimental studies in building physics with focus on ventilation and energy saving. The garage with doors facing south is located in the extended south part of the cellar as shown in Figure 1.

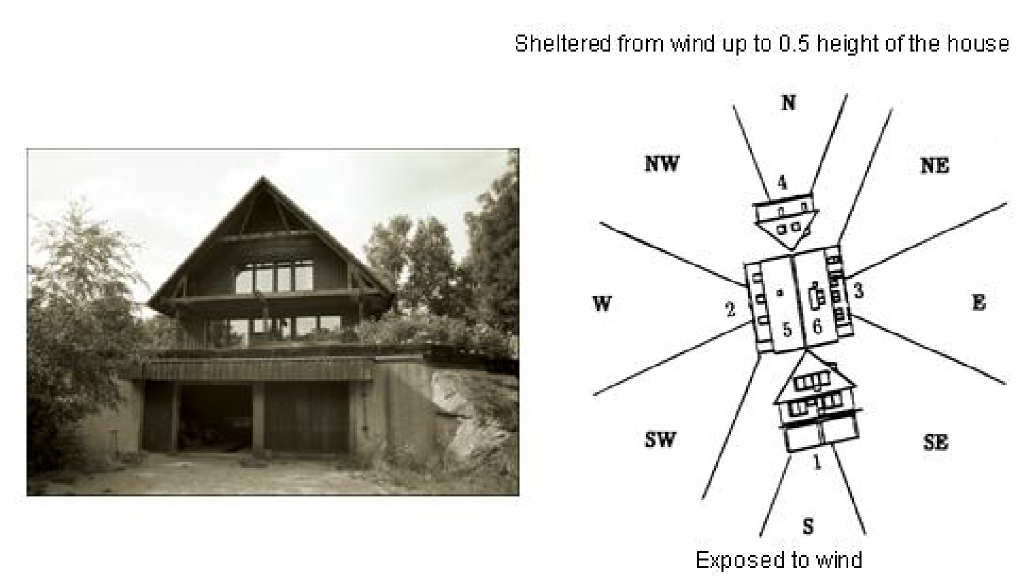

Figure 1. Object of the study

Measurement program

The following parameters have been measured, as is shown in Figure 2: leakage characteristics of the house using blower door tests, mean value of pressure difference across the 6 building components with Validyne pressure transducers, wind speed and wind direction with the anemometer located on a small hill about 25 m from the house, internal and external temperatures. The measurement program was carried out for 8 months. As a result, hourly mean data have been obtained.

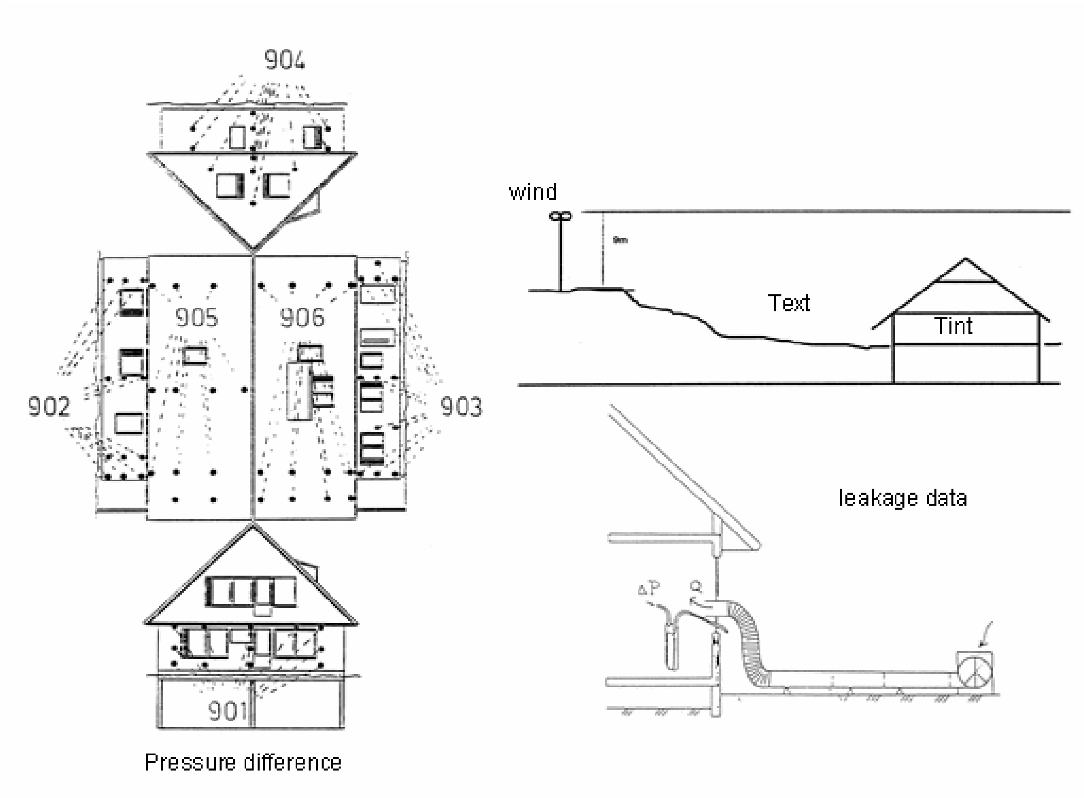

Figure 2. Measurement program for validation of probabilistic model of air infiltration

The results of the pressure drop measurements have been used to calculate the air exchange through the envelope. An opening under the garage door has been treated separately in the calculation model (see Pietrzyk & Hagentoft, b, Pietrzyk, 2000).

Case study with the help of PROMO model

The modelling flow for the PROMO model together with the results obtained is shown in Figure 3. For each wind direction sector the modelling procedure has been performed. Eventually, two cases have been distinguished. The first one considering those wind direction sectors to which the opening under the garage door has been exposed and the second one concerning all remaining wind direction sectors. The probability density functions of the air change rate for these cases approximated using the first order reliability method FORM (Pietrzyk & Hagentoft, a) are presented in Figure 3. For the case one (the opening exposed to wind) a log-normal probability density function has given the best fit according to Kolmogorov-Smirnov test with significance level of 0.05. For the other case, a normal probability density function has been fitted.

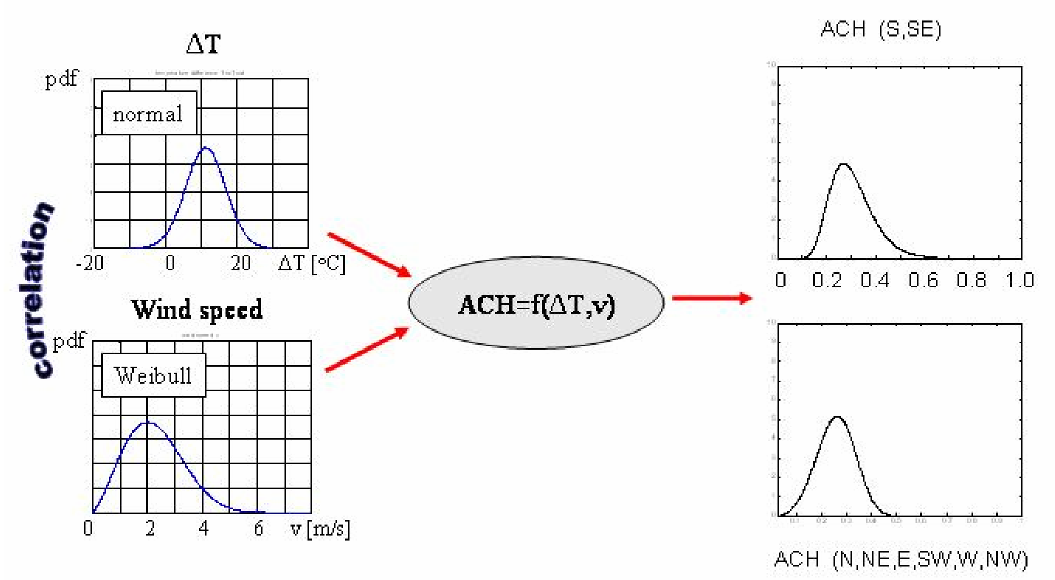

Figure 3. Modelling flow and the results obtained from probabilistic approximations using FORM

Validation of the PROMO model

The probabilistic model of air infiltration has been validated on the basis of full-scale pressure difference measurements carried out on the test house. The validation model is described in (Pietrzyk & Hagentoft, b). The results of air change rate calculations have been shown in Figure 4 in the form of histograms and probability density functions fitted to those results. They present the same cases as approximated with the help of the PROMO model. The mean value, the standard deviation, the skewness and the peakedness of validation results agree with the moments calculated for the probabilistic approximations. Eventually, the recommended types of distributions are similar (see Figures 3 and 4).

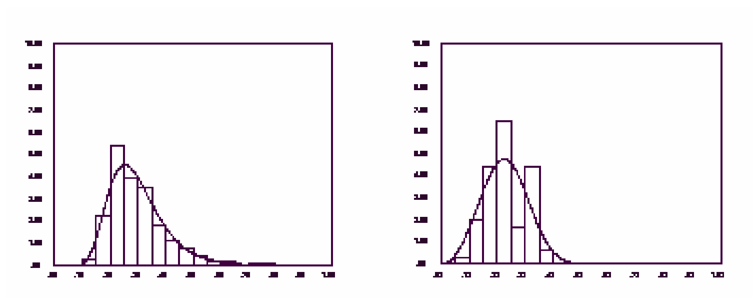

Figure 4. The results of validation of the PROMO model in the form of histograms and probability density functions of ACH estimated for the case 1- left (wind directions: S, SE) and the case 2 - right (other wind directions).

APPLICATION OF PROMO RESULTS

The probability density functions of air change rate can be used to evaluate the reliability of natural ventilation for a building but also to evaluate the reliability of the energy performance of the building envelope. In the context of energy balance, air infiltration constitutes one of many possible processes of heat exchange between the interior and the exterior of a building. Air infiltration can also be considered from the point of view of its influence on the properties

(thermal and structural) of building components. Some parameters of the buildings, usually treated as deterministic, are in reality dependent on climate-induced airflow through the structure and those should be treated as random variables. For some building technologies, especially those involving lightweight timber frame with mineral wool filling, and loose mineral wool layers for roof insulation one can speak about the dependence of the thermal properties of building components on air infiltration. It is very clear for the, so called, "dynamic wall" (Anderlind & Johansson, 1983), specially designed to save energy. The interaction between thermal transmittance and airflow through the components should be considered while calculating heat loss through a building envelope. The thermal transmittance becomes the most interesting parameter that can vary with the climatic parameters and should be treated as a random variable. Probabilistic description of air filtration through the wall is an important input to probabilistic model of thermal transmittance (Pietrzyk & Hagentoft, 2004).
Eventually, reliability of energy performance for building envelope components exposed to various environmental and climatic conditions can be analysed. Different design options concerning also the effect of air infiltration on variations of thermal transmittance of the envelope can be calculated in the form of probability density functions of heat loss characterising energy performance of the envelope. Additionally, different ventilation strategies can be considered in terms of reliability (Pietrzyk, c).

CONCLUSIONS

The probabilistic model PROMO for the approximation of probability density function of air change rate for a naturally ventilated house on the basis of the probabilistic description of climatic data is developed and validated with the help of the results of full-scale pressure difference measurements.
The probability density functions of air change rate can be used to evaluate the reliability of natural ventilation for a building but also to evaluate the reliability of the energy performance of building envelope.

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