OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS

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(Title) **PROBABILISTIC ANALYSIS OF AIR INFILTRATION IN A SINGLE FAMILY HOUSE**

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SYNOPSIS

A Probabilistic model of air change rate in a single family house based on full-scale measurements has been developed. The probability of air change rate exceeding certain prescribed limits (risk of improper ventilation or excessive heat flow) is evaluated by utilising the distribution function based on calculated air flow rate. In this way the results are expressed in terms of the R-S model generally used in the safety analysis of structures. In particular, the probability of excessive and/or insufficient air infiltration can be expressed in terms of safety index β to describe the reliability of the building with respect to natural ventilation. The probability density functions for the air change rate have been established for different wind directions

Two methods of reducing the risk of unhygienic conditions have been studied. The first one is based on introducing extra small openings uniformly distributed over the building envelope and providing a fully naturally ventilated system. The second method consists in introducing mechanical exhaust ventilation system coupled with natural ventilation. Probability distributions of air change rates have been analysed for these two cases.

1. INTRODUCTION

Probabilistic model of air infiltration has been developed from full-scale measurements carried out on a single family timber framed detached house located on the outskirts of Gothenburg Figure 1 shows the plan of the house seen from above togather with eight wind direction sectors. Details of the test house and the model presented herein are based on the work in reference 1.

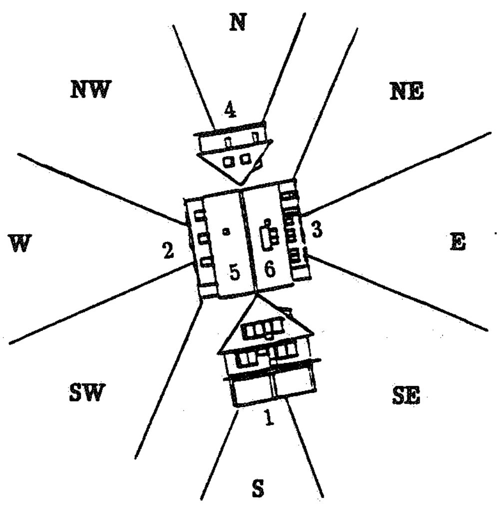

Figure 1. *Plan of the test house and sectors for wind direction*

Wind velocity and direction togather with pressure differences across the building envelope and outside and inside temperatures were recorded continuously for a period of eight months. Measurements of the airtightness of the building by *blower door test* method and the measurements of the air change rate by *tracer gas decay* technique have also been performed.

2. STATISTICAL PROPERTIES OF THE AIR CHANGE RATE

The air change rate per hour ACH is calculated from the air flow rate Q and the volume V of the enclosure and is defined as:

$$ACH = Q / V$$

The air flow rate is a function of the pressure difference and the leakage properties and is given by:

$$Q = K A \sqrt{\Delta p}$$
$$K = f(Re)\ \alpha \sqrt{2/\rho}$$

Where K is a leakage function of pressure difference ($\sqrt{m^3 / kg}$), $f(Re)$ is a coefficient of frictional resistance, α is the relative leakage area (A_1 /A) and ρ is the air density. Δp is the pressure difference. The air flow rate Q depends on the

- Climatic parameters (wind velocity, wind direction and temperature difference)
- Structural parameters (leakage characteristics of the building)
- Serviceability parameters (internal temperature, intentional openings etc).

All of these parameters should be treated as random variables with their own statistical properties. Wind velocity variations in time can be described by two parameter ***Weibull*** distribution. The full-scale measurements of air temperatures have shown that the temperature difference between outside and inside of the house follows *Normal* distribution. Leakage properties of the house can be different depending on the wind direction. For the openings, where a boundary flow occurs, leakage properties can vary significantly with the magnitude of pressure difference across the building envelope. It implies that the leakage properties become function of randomly distributed pressure differences.

Model of air change rate ACH based on the full-scale pressure measurements has been developed by assuming that:

- the mean rate of air flow through the leaks is determined by 10-minute mean pressure differences across the building envelope,
- the amount of air entering and leaving the house is in balance during the whole measurement period,
- the leakage area is uniformly distributed over the building envelope except one large opening on the south side of the building,

Air change rates have been evaluated as 10-minute mean values for each hour of the measurement period based on separate estimation of the amount of air entering and leaving the house. Histograms of air change rate have been calculated for eight wind direction sectors.

Air change rate for wind blowing from the south and south-east directions is approximately *log-Normally* distributed. Air change rates for other wind directions seem to follow *Normal* distribution . Because of different types of distributions of air change rates for certain wind directions, further analysis has been done within the groups of homogeneous data.
The probability density functions have been fitted to air change rates for two cases:

Case 1. Large opening is situated on the windward side and wind direction $\theta_1 = \{S, SE\}$

Case 2. Large opening is not situated on windward side and wind direction $\theta_2 = \{N, NE, E, SW, W, NW\}$

For *Case 1* , three-parameter *log-Normal* distribution with threshold of 0.05 has been fitted to the data of *ACH* as shown in figure 2. For *Case 2, Normal* distribution truncated at 0.05 has been fitted as plotted in figure 3. These two distributions have been checked by the Kolmogorov test at significance level of 0.05.

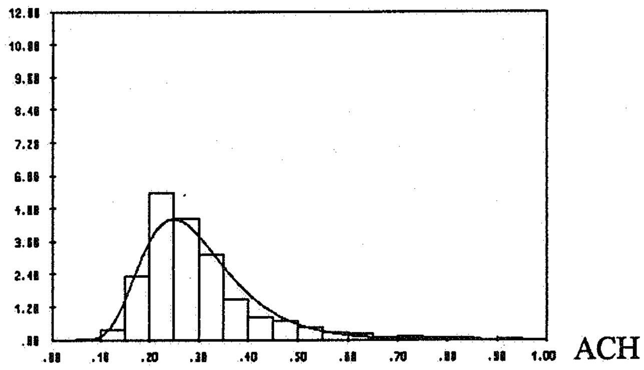

Figure 2. *Histogram and the probability density function fitted to ACH for Case 1*

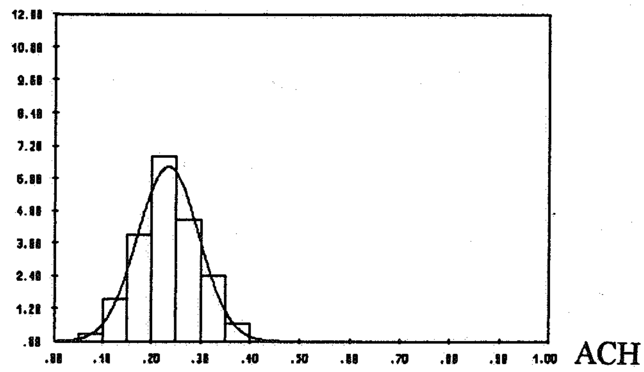

Figure 3. *Histogram and the probability density function fitted to ACH for Case 2*

3. RISK ANALYSIS OF AIR INFILTRATION IN A BUILDING

Malfunctioning of ventilation in the house occurs when air change rate is less than allowable minimum value R_1 leading to unhygienic conditions or is higher than the maximum value R_2 resulting in unnecessary heat losses. On the basis of estimated distribution of air change rate probability of *ACH* exceeding certain limits R_1 and R_2 can be evaluated . The problem of air flow through the building envelope is considered in terms of load-resistance model , where resistance R describes the serviceability limit states R_1 and R_2 and the load effect S expresses the air change rate. Serviceability conditions are not fulfilled when $S<R_1$ or $S>R_2$. Figure 4 shows a hypothetical model for the serviceability limit state for *ACH.*

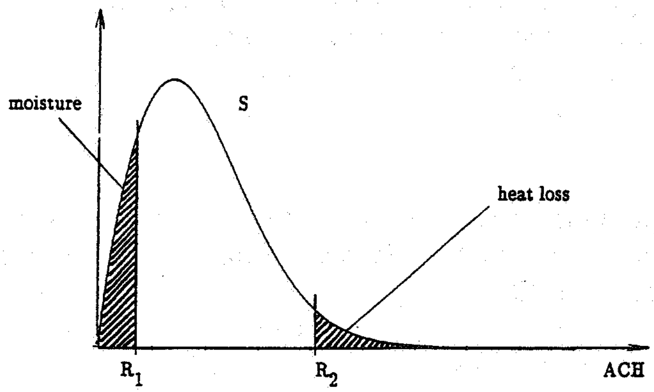

Figure 4. *Modelling of serviceability limit states for ACH.*

For assumed allowable limits R_1 and R_2, safety indices β_1 and β_2 can be calculated from the standardised probability density function of *ACH*. Since there are two different probability density functions which have been estimated for different wind direction sectors,the method of calculation of safety indices is presented for *Normal* and *log-Normal* distributions in Table 1.

Distribution function	***Safety Index*** β_1	***Safety Index*** β_2
Normal	$(\mu_x - R_1)/\sigma_x$	$(R_2 - \mu_x)/\sigma_x$
Log Normal	$[\mu_y - \ell n(R_1 - y_0)]/\sigma_y$	$[\ell n(R_2 - y_0) - \mu_y]/\sigma_y$

Table 1. Safety Indices for *Normal* and *log-Normal* distributions

The probability density functions can be read from the standard normal distribution tables.

The assessment of the allowable values of R_1 and R_2 are governed by the Code of Practice as well as a subjective estimation based on economy. According to the Swedish Code of Practice the minimum value of air flow is 0.35(l / s) per 1m^2 of the floor area which means that 0.52 changes per hour is the minimum requirement for the test house. Risk of air change rate less than prescribed limit R_1 is obtained by calculating the conditional probabilities for different wind direction.

$$P(ACH<R_1) = P(\theta=\theta_1) \times P(ACH<R_1 \mid \theta=\theta_1) + P(\theta=\theta_2) \times P(ACH<R_1 \mid \theta=\theta_2)$$

where $P(ACH<R_1 \mid \theta=\theta_1)$ is the conditional probability for *log- Normal*
and $P(ACH<R_1 \mid \theta=\theta_2)$ is the conditional probability for *Normal* distribution.

For R_1=0.52 , the probability of unhygienic conditions for the test house is equal to 0.99 if the natural infiltration is the only source of supply.

4. THE INFLUENCE OF IMPROVED VENTILATION ON THE AIR CHANGE RATE DISTRIBUTION

Two methods for reducing the risk of unhygienic conditions have been studied . The first one is based on introducing small openings uniformly distributed over the building envelope and providing a fully naturally ventilated system. The second method consists of introducing extra exhaust mechanical ventilation. A brief description is presented below.

First method
The air change rate is approximated as a linear function of the area of the openings in the buildings envelope. Figure 5 shows that the increase in the mean air change rate results in the decrease of risk of inadequate ventilation. Figure 5 also shows the influence of type of probability density function on the *ACH*. It can be noted that for p_l below 10^{-2} the air flow rate is larger for *Normal* compared to *log-Normal* distribution.

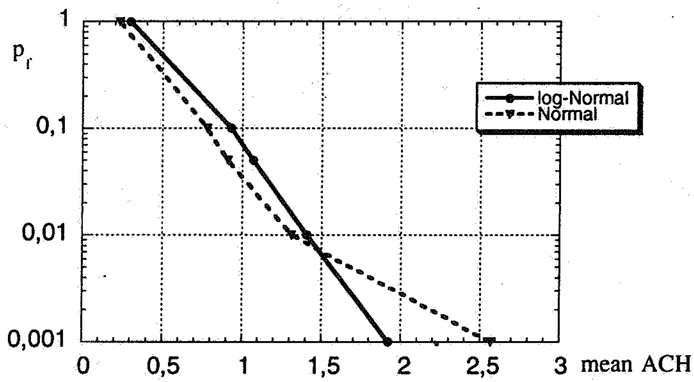

Figure 5. *Risk of unsatisfactory ventilation P(ACH<0.52) of ACH for naturally ventilated house*

The mean value of air change rate and proper size of openings required to reduce the risk of inadequate ventilation to p_l has been calculated from the conditional model and it is shown in Table 2.

Second method
In order to reduce the risk of unhygienic conditions in the house one can provide some extra air supply , e.g. by means of mechanical exhaust ventilation. The total value of air change rate ACH_{tot} is obtained by adding the contributions from both natural and exhaust ventilation.

$$ACH_{tot} = \sqrt{ACH^2_{nat} + ACH^2_{exh}}$$

We assume that the air change rate caused by exhaust ventilation is a deterministic quantity defined as $c=ACH_{exh}$ and that natural ventilation is a random quantity defined as $x=ACH_{nat}$. The probability density function for total air change rate $z=ACH_{tot}$ can be written as:

$$f_z(z) = [z/\sqrt{(z^2 - c^2)}]\, f_x(\sqrt{z^2 - c^2}) \qquad \text{for } x>c$$
$$z = \sqrt{x^2 + c^2}$$

The first order estimates of the expected value μ_z and the variance σ_z of the variable z can be obtained by expanding the function in Taylor series about the mean μ_x and retaining the first-order term of such expansion which results in:

$$\mu_z = \sqrt{\mu^2_x + c^2} \quad \text{and} \quad \sigma^2_z = \sigma^2_x \, \mu^2_x / (\mu^2_x + c^2)$$

For assumed risk of failure, the necessary value of the efficiency of the exhaust ventilation and the actual mean and standard deviation of ACH_{tot} have been calculated in Table 2 . a is the size constant of the intentional openings provided for increasing the rate of air infiltration in order to achieve certain level of safety.

p_I	β_I	ACH_{nat}		a	ACH_{tot}		ACH_{exh}
		μ_x	σ_x		μ_z	σ_z	
0.001	3.08	2.42	0.80	9.7	0.64	0.034	0.59
0.01	2.32	1.34	0.44	5.4	0.61	0.035	0.59
0.1	1.27	0.82	0.27	3.3	0.57	0.038	0.51
0.989	-4.68	0.25	0.08	1.0	0.25	0.086	

Table 2 *Calculation of ACH for assumed probability and calculated from experimental data (shaded area)*

Figure 6 shows the influence of two different types of ventilation in the test house.

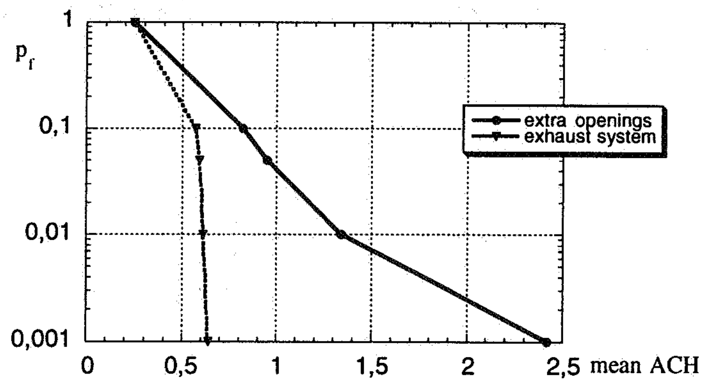

Figure 6. *The risk of unhygienic conditions $P(ACH_{tot}<0.52)$ for the mean value of ACH for the naturally ventilated house and for the house with exhaust ventilation*

The *first method* consists of increasing the natural ventilation, while the *second method* involves the use of mechanical exhaust system. For given risk of unhygienic conditions (e.g. 10^{-2}) one needs significantly higher mean air change rate for purely ventilated house (1.3/h) than for a house with exhaust system (0.6/h). The random character of climatic conditions has significant influence on the natural ventilation. The coefficient of variation of air change rate for the naturally ventilated test house has been calculated as 0.34. Coefficient of variation for air change rate for total ventilation (exhaust and natural) I_Z is obtained from:

$$I_z = I_x / [1 + (c^2 / \mu^2_x)]$$

A plot of ratio of air change rates caused by mechanical exhaust ventilation and natural infiltration is shown in Fig.7. Introduction of exhaust system causes significant decrease in the coefficient of variation of air change rate compared to the naturally ventilated house.

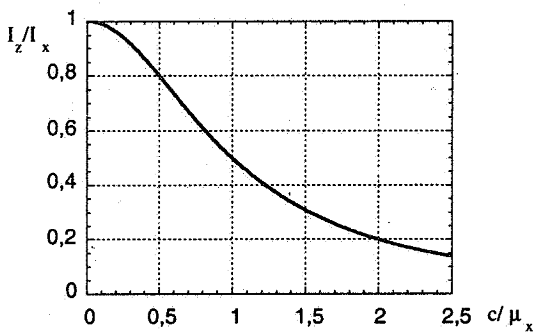

Figure 7. *Relationship between ratio I_z/I_x and ratio a/μ_x*

Figure 8 shows the probability density functions plotted from the data given in Table 2 concerning the assumed risk of inadequate ventilation p_I of 10^{-1} and the experimental data shown shaded. The results show that for the house under consideration , one needs to introduce additional openings in the envelope of the building with an equivalent area of about 3.3 times than original one or to switch on the mechanical exhaust system with efficiency of 0.51/hour for adequate air supply. This is true even if the contribution of natural driving forces is included in the model. The mean value of air change rate calculated for the two methods are different. For pure natural ventilation the mean value is 0.82/hour and for the combined effect of natural and exhaust ventilation it is equal to 0.57/hour. It means that for certain specified risk of unhygienic conditions the naturally ventilated house should be better ventilated than in the case of exhaust system

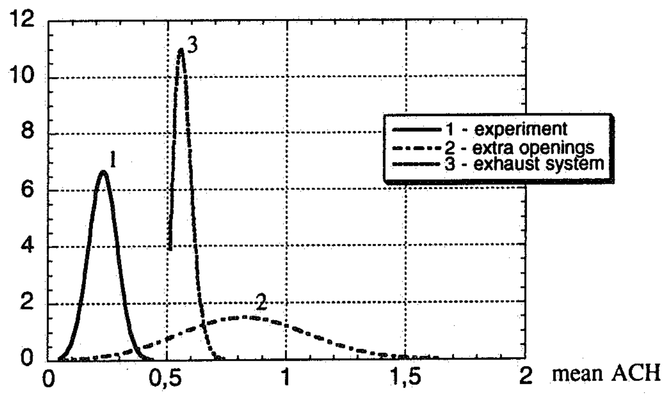

Figure 8. *Probability density functions of ACH: for data calculated from the experiment (1), based on risk level of p_I = 0.01 for improved natural ventilation (2) and based on risk level of p_I = 0.01 for combined effect of natural and exhaust ventilation (3) as shown in Table 2.*

5. CONCLUSIONS

The main conclusions of the work are:

1. Probability density functions of *ACH* are estimated for different wind directions and the results show the influence of wind on theirs shape when the leakages are non uniformly distributed over the building envelope. For cases where no large openings are situated on the windward side, the distribution of air change rate is found to be *Normal*. When a large opening is present on the windward side, the air change rate follows *log-Normal* distribution.

2. Risk analysis of malfunctioning of ventilation is carried out on the basis of conditional model of ACH and it considers two aspects dealing with insufficient and excessive ventilation. The assessment of the allowable values R_1 and R_2 *(R_1- limit for risk against unhygienic conditions, R_2 - limit for risk of unnecessary heat loss)* is a matter of regulations in the Code of Practice (R_1) as well as subjective estimations based on economical costs (R_2).

3. The risk of improper ventilation has been presented in the form of safety index β. Risk of uhygenic conditions in the test house of order 10^{-3} ($\beta \approx 3.$) depends on the type of distribution of *ACH* *Normal* and *log-Normal* which are used in presenting the probabilistic model.

4. The coefficient of variation of *ACH* for the house with exhaust ventilation is significantly smaller than for naturally ventilated house. For a certain level of risk of unhygienic conditions the naturally ventilated house should be better ventilated than in the case of using exhaust system.

6. ACKNOWLEDGEMENTS

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7. REFERENCE

[1] PIETRZYK KRYSTYNA *Risk Analysis of Air Infiltration in a Single Family House*. Chalmers University of Technolgy, Gothenburg Sweden, 1995 (Tek.Lic. Thesis)