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A DYNAMIC MODEL FOR SINGLE-SIDED VENTILATION

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ABSTRACT

The aim was to develop a simple dynamic model for predicting air exchange caused by short time single-sided ventilation and necessary window opening time in classrooms. Tracer gas measurements have been made in a full-scale room. The comparison indicates that the model can be used when rough estimates of air exchange are of interest.

KEYWORDS

Window opening, single-sided ventilation, indoor climate, schools, model, measurement, tracer gas method.

INTRODUCTION

Ventilation is an important factor when a satisfactory indoor environment is to be achieved and good conditions are to be provided for people. This is especially important for people who suffer from allergic symptoms. In classrooms both insufficiency of fresh air and high room temperatures are a problem. Window opening can be a useful addition to the existing mechanical ventilation system in order to solve these problems. There should however always be an existing ventilation system where window opening can only be a complement. The disadvantages of this kind of ventilation is; that the supply air is unfiltered and unheated, heat recovery is difficult or impossible and the mechanisms are uncontrollable and variable. The disadvantage due to cold draught can be avoided by opening windows during the breaks when there is nobody in the classroom. In some conditions window opening is not advisable, for instance when there is a large amount of pollen or situated close to heavy traffic.

The main purpose of this project was to study window opening and its application in classrooms. The whole work, presented in a licentiate thesis (Nordquist, 1998), consists of three parts, the first of which will be presented in this paper. In the first part measurements were made of air exchange through an open window using tracer gas. A relationship for the time dependent airflow was suggested. The airflow decreases during the window opening period and with the help of the model an appropriate opening time can be decided.

In the second part, not presented here, computer- calculations were made of the impact of window opening on the airflows distributed by a mechanical supply and exhaust ventilation system. The total air exchange is increased in the room during the opening period. In the third part a questionnaire answered by teachers in Malmö, Norrköping and Umeå about their window opening behaviour was presented. The questions related to the frequency of window opening, the reasons for and against this. One out of two teachers open the windows during every break all through the year. The most common factors for window opening were bad air and high room temperatures and the factors for avoiding it were cold outdoor air and noise from outside.

MATERIAL AND METHODS

Dynamic Model

When air is exchanged through an opening the driving force; the temperature difference between the outdoor and the indoor air, decreases as the outdoor air enters the room. This phenomenon has been partly studied for open doors by Kiel and Wilson (1986) and Nielsen and Olsen (1992). The model of Kiel and Wilson assumes a period of constant flow until the outdoor air level reaches the middle of the opening. Then the constant flow is assumed to decrease exponentially with time until the upper level of the opening is reached. This is an approximation of the physics. The physics without mixing can however be treated correctly as will be shown in this paper, with constant flow until the lower level of the opening is reached and then a decreasing flow to zero until the upper level of the opening is reached. Single-sided ventilation has also been studied in the European PASCOOL project (Santamouris et al, 1996). Passive night cooling were studied and thermal dynamics were modelled with computer programs. This paper presents an explicit expression how to calculate air exchange for short time window opening.

The aim is that the model should give typical values of air exchange and window opening time, to be used when few parameters of a building are known. The model assumes that openings are vertical and that the mechanism for the air exchange is the temperature difference between outdoor and indoor air. Heat convection from enclosures during window opening is not taken into account, this may apply when windows are opened for short periods. If windows are opened for a long time the enclosures will be cooled, which is not advisable for energy-saving reasons during heating season. It is also assumed that the outdoor air temperature is lower than the room air temperature. Wind is not considered in the model.

Two models have been developed. The first model assumes no mixing between room air and incoming outdoor air. The second model assumes a total mixing in the room. In this model the indoor temperature is decreased during the time the window is open. It is expected that conditions would in reality be between these two extreme models. The first model shows the lowest air exchange and will be presented in this paper in the following section. The calculation is divided into two time spans. During the first interval the outdoor air is assumed to fill the room air volume below the opening and during the second phase the room air volume in front of the opening is assumed to be replaced with outdoor air, leaving a volume of unventilated air above the opening.

During the first phase the flow is constant and may be expressed as follows (Awbi, 1991)

$$q = C_d \frac{B}{3}\sqrt{g' H_0^3} \qquad (\mathrm{m^3/s}) \tag{1}$$

where q = flow through window (m^3/s)

$C_d = 0.4+0.0045(T_i-T_u)$: opening orifice coefficient (-) (Kiel et al, 1986) (2)

B = opening width (m)

$$g' = g\frac{\Delta\rho}{\bar{\rho}} = g\frac{2(T_i - T_u)}{(T_i + T_u)} \quad (m/s^2) \tag{3}$$

H_0 = opening height (m)

T_i = indoor temperature (K)

T_u = outdoor temperature (K)

The outdoor air volume V_{a1} which has entered the room through the lower part of the opening during the time t_1 (s) is

$$V_{a1} = qt_1 \quad (m^3) \tag{4}$$

The same volume of room air is assumed to have passed trough the upper part of the opening.

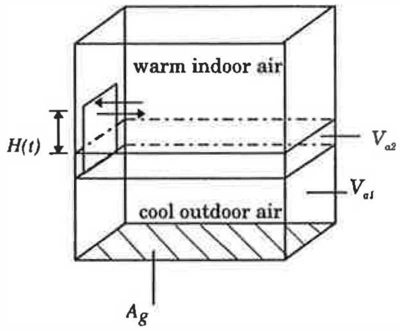

Figure 1: The outdoor air is assumed to first fill the room air volume below the opening (first phase). During the second phase the room air volume in front of the opening is assumed to be replaced with outdoor air. During the second phase the flow is assumed to decrease. The height through which the air is exchanged is a function of time as shown in the figure.

The second phase ends when the exchange stops, which is when the room volume up to the upper limit of the opening is filled with cold outdoor air. As no mixing is assumed to occur, the room air above the opening will not be ventilated. The air flow rate during the second phase is written as

$$q(t) = C_d\frac{B}{3}\sqrt{g' H(t)^3} \quad (m^3/s) \tag{5}$$

and the height $H(t)$ can be solved as

$$H(t) = \frac{1}{\left(\frac{at}{2} + \frac{1}{H_0^{0.5}}\right)^2} \quad (m) \tag{6}$$

where t = window opening time during phase 2, t=0 when phase 2 starts (s)

$$a = C_d\frac{B}{3A_g}\sqrt{g'} \tag{7}$$

where A_g = floor area (m^2)

The outdoor air volume V_{a2} which has entered the room during the second phase is given by

$$V_{a2} = (H_0 - H(t)) \bullet A_g \quad (m^3) \tag{8}$$

The total amount of exchanged air V_a during both phases is calculated

$$V_a = V_{a1} + V_{a2} \quad (m^3) \tag{9}$$

Measurements

Measurements have been made in a full-scale room in a test building situated close to the department of Building Services. The floor area was 10.8 m^2 (3x3.6) and the room volume was 26.6 m^3. A side-mounted casement window with a width of 1.05 m and a height of 1.15 m was opened by a telescopic arm for different time intervals. The room was facing south. The test cycle was as follows: The room was filled with NO_2 until a well mixed concentration of about 1000 ppm was reached. The supply was stopped and the decay of the tracer gas due to infiltration was measured for 10 minutes. During the supply and decay of the gas three fans were used to mix the air. Then the fans were turned off and the window was opened and held open for 1, 2, 3, 4 or 5 minutes. After closing the window the fans were turned on again. The decay was measured for another 10 minutes and one test was concluded.

A gas analyzer (Binos 4b), was used to determine the concentration of tracer gas sampled from 2 locations in the room. The measuring equipment was supervised by a computer. The indoor and outdoor temperature were measured to determine the temperature difference needed in the model calculations. The temperatures were measured with 9 thermocouples type T. One was placed outside and the other eight were spaced 0.3 m apart on a vertical rod placed in the middle of the test room. The indoor temperature T_i used in the model was measured just before the window was opened. T_i was calculated as the mean value of all the 8 thermocouples.

The fans were not working when the window was open in order not to disturb the air movement. In the calculation only the tracer gas concentrations before and after opening were used, as the mixing was not uniform during the time the window was open. The air exchange during the open period was assumed to be proportional to the difference in concentration right before and after the opening. The exchanged amount of air was calculated for two different cases. One case assumed no mixing between the room air and the outdoor air and the other assumed total mixing. The case with no mixing will be presented here.

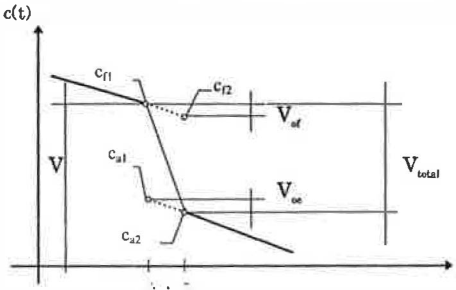

Figure 2: The gas concentrations c_{f1}, c_{f2}, c_{a1}, c_{a2} were calculated with linear regression from the measured concentrations before and after the window opening period. The dotted lines are extrapolated from the linear regression equations. The air volume V_{total} is the whole volume of air which is exchanged during the time the window is open. V_o is the volume which is exchanged due to other ventilation during airing. The difference between V_{total} and $(V_{of}+V_{oe})/2$ is the exchanged air volume V_a due to window opening.

RESULTS

Comparison between model and measurements

Measured and calculated values are presented in Figures 3 and 4. The outdoor conditions during the different measurements were fairly similar. The temperature difference was within the interval 8-12 K during 21 of the 24 measurements and the wind speed was between 2-6 m/s during 22 of 24 and the wind direction were from NW, W and SW towards SE, E, NE. The wind condition were given as hourly values/ mean values over one hour. No parametric adjustments have been made in the model.

The model presented by Kiel and Wilson (1986) has also been applied to the conditions during the measurements, assuming constant flow when the outdoor air fills the room volume below the opening.

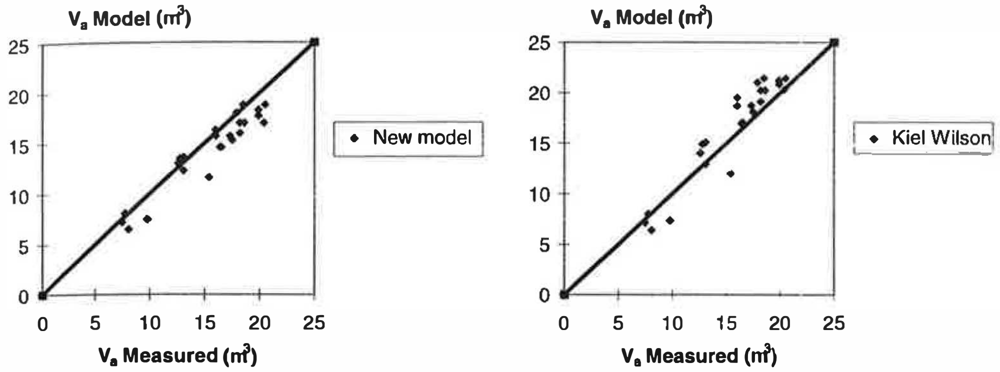

Figure 3: The calculated air volumes as a function of measured values.

Figure 3 shows that in most cases the new model slightly underestimates the measured air exchange. It also shows that the model of Kiel and Wilson and the new model give values of the same order of magnitude.

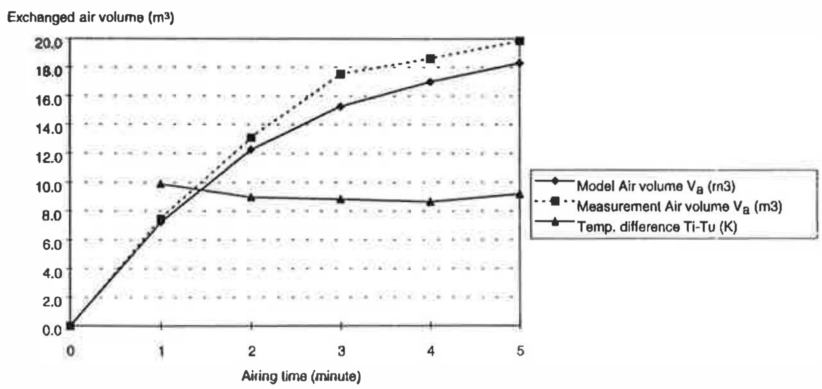

Figure 4: Calculated and measured air volumes. Window open for five different periods; 1, 2, 3, 4 and 5 minutes respectively. No mixing between room air and outdoor air is assumed.

Figure 4 shows the result for one of the five sets of measurements which is representative for the results. The measurement results in Figure 4 show that the exchanged air volumes are decreased during the window opening period which means that the air flow through the window opening decreases.

DISCUSSION

The model and the measurements show a congruence in window opening pattern with decreasing air flow. As regards advisable window opening periods the decrease shows that the window should be open for only shorter periods as the amount of air exchanged will be less and less the longer the window is kept open. In most cases the new model underestimates the measured air exchange by about 10-20%.

The model is, as mentioned before, designed to give relatively rough estimations. The contribution of wind to the air change is not included. If a rough value is aimed for, without considering orientation and shape of the building, it is difficult to account for changes in wind speed and wind direction. At high wind speeds it is not advisable to use the model. Heat convection from the enclosures to the air is neglected in the model. No consideration is given to the possible effect of the mechanical ventilation system. The measurements are made in a room that is relatively small compared to a classroom.

The comparison indicate that the model can be used when rough estimates of air exchange by window opening are of interest. Continued research is however needed in order to verify the model. Measurements should also be conducted in bigger rooms, such as classrooms. Additional measurements for longer periods would also be of interest. The model considers only one opening. It would also be of interest to study air exchange with several openings.

ACKNOWLEDGEMENTS

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REFERENCES

Awbi H. B. (1991). *Ventilation of Buildings.* UK: London, Chapman & Hall

Kiel D. E., Wilson D. J. (1986). *Gravity driven flows through open doors.* Paper 15. Proc. of the 7th AIC Conference, Stratford-upon-Avon, United Kingdom

Nielsen A. F., Olsen E. (1992). *Luftströmmer og varmetap gjennom porter.* FORUT Teknologi AS Norway

Nordquist B. (1998). *Vädring i skolor - ett komplement till normal ventilation?* (Window opening in schools - a complement to existing ventilation?) (in Swedish). TABK—98/1014, Dept. of Building Science, Lund Institute of Technology, Sweden

Santamouris M., Dascalaki E., Allard F. (1996). *Natural ventilation studies within the frame of PASCOOL project.* Proc. of the 17th AIVC Conf., Gothenburg, Sweden