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Ventilation and Energy Loss Rates After Opening a Window

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Introduction

Multizone air infiltration and ventilation modelling is in progress, both by the development of computer programs with a modular structure and a user friendly interface (Ref.1) and by R & D on the algorithms which can be used as a basis for those modules (Refs.1,2).

In building simulations it is important to be able to evaluate user behaviour on the ventilation and energy loss rates. This implies that one should be able to predict firstly, how often and how long occupants open and close windows, and secondly how ventilation and energy loss rates depend on building parameters, meteorological parameters and opening time.

As a solution to the first problem, a stochastic model of user behaviour has been developed (Ref.3), which generates time series of window opening angles with the same statistics as the measured openings for the heating period.

On the other hand, previous discussions of the ventilation rates through a given single large opening (Refs. 4-9), showed that to calculate the stack effect it is sufficient to know the inside-outside air temperature difference (T_{in}-T_{out}), while for the calculation of the influence of the wind one relies on empirical relations (Refs.4,7). In all these discussions, the ventilation rate (V) is found from the velocity in the window opening and the window size, while the heat loss rate by single sided ventilation equals

$$Q = c\rho V(T_{in} - T_{out}) \tag{1}$$

In this note we discuss the problem (concealed by the latter statement) of calculating the inside air temperature which varies with time and is, when not measured directly, in general not known. The inside air temperature (T_{in}), which is in between the outside air temperature (T_{out}) and the building temperature, can be calculated with a simple model recently developed and validated for a few real cases (Refs.10,11). The new ventilation model takes heat transfer between the air and walls into account, uses a dynamic wall thermal model and includes as limiting cases the situations where (Figure 1):

(i) the cold air enters as a gravity wave, replaces the warm air completely (adiabatic walls, no heat transfer), and the stack ventilation comes to a halt after one air change (Refs.5,8).

(ii) the entering cold air is warmed up to the building temperature (infinite heat transfer), the stack ventilation rate is constant and calculated from the temperature difference between the outside air and the building (Refs.4,6,7).

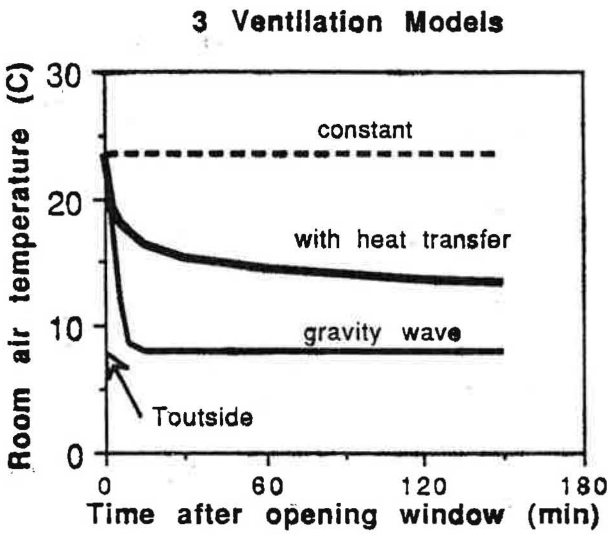

Figure 1: Predictions of three ventilation models compared for a particular case. The constant temperature and the gravity wave model are limiting cases of the model including heat transfer.

Mechanisms

The model follows naturally from the following observations on an empty room in thermal equilibrium with the surrounding building structure: after opening a single window to the cold outside one observes first a sudden drop in air temperature, followed by a slow decrease in temperature. One notes that the wall surface temperature is higher than the air temperature and that the slow decrease in air temperature is due to a decrease in wall surface temperature. Moreover, it is found that the relative magnitude of the initial temperature drop is larger in smaller rooms and for larger window areas.

Finally the new model (Figure 2), couples the heat flow rate through the aperture (Equation 1) with heat transfer between the air and the walls (T_{in} drops below T_w) and with a wall surface temperature $T_w(t)$, decreasing with time. The model introduces two new parameters, (1) the heat exchanging wall surface area and (2) the average thermal permeability of the walls.

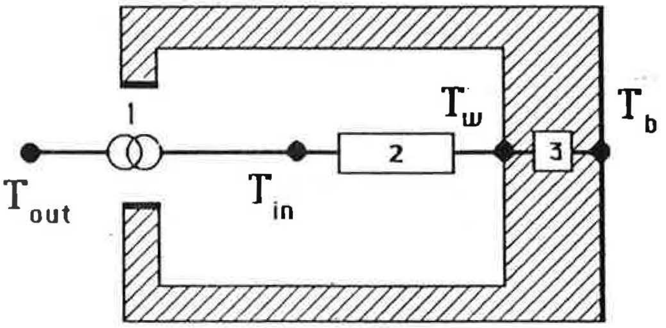

Figure 2: Ventilation and thermal models coupled in a four node network. 1.Heat source Q (Equation 1). 2.Boundary layer resist $1/C_2S_i\,h_c$(Equation 3). 3.Dynamic thermal wall rsistance (Equation 4). $T_b = T_w(0)$, initial wall tempeure.

Ventilation. The heat loss rate due to ventilation is calculated with Equation 1, and for the ventilation rate one could take the expressions proposed in References 4,7 or 9. The model has been tested for large inside outside temperature differences and small wind velocities. In this way the uncertainties concerning wind induced ventilation were avoided. For the single sided ventilation through an opening of height H and width W, the stack effect equation is used with a discharge coefficient $C_1 = 0.6$:

$$V = \tfrac{2}{3}(WH/2)C_1\sqrt{(gH(T_{in}-T_{out})/T)} \qquad (2)$$

Heat transfer. The temperature difference between the air and the wall surface, T_{in}-T_w, is described by a heat transfer coefficient h, and equals q/h, where q is the heat flux density. A fixed value of $h = (6 \pm 1)\ W/m^2K$ appeared to be consistent with the measurements (Refs.10,11). The value of q is calculated from the total heat flux Q (Equation 1), and the heat exchanging wall surface area C_2S_i:

$$T_w - T_{in} = Q/C_2S_i.h \qquad (3)$$

The coefficient C_2 is the fraction of the total wall surface area S_i, which is active in the heat transfer process (Refs.10,11). The meaning of C_2 is illustrated in Figure 2. The larger the distance between the window and the ceiling, the smaller is C_2 (Figure 3b).

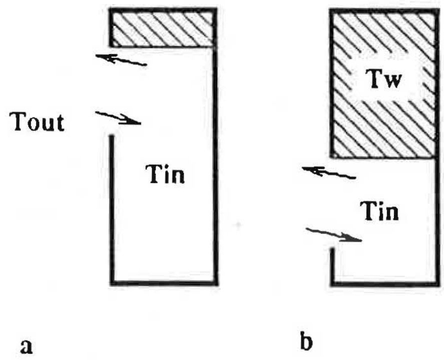

Figure 3: Above the upper level of the window warm air is trapped. This remains at the same temperature as the wall, T_w, and the ceiling and walls above the window level do not cool by convection. The coefficient C_2 is about 0.8 in a and 0.4 in b.

Wall thermal model. Until opening the window at time t=0, the walls are considered to be in thermal equilibrium with the building at temperature T_b. For the heat flux density q, the wall surface temperature T_w becomes an explicit function of time. For a wall characterized by a thermal permeability $\beta = \lambda\rho c$, a simplified model for $T_w(t)$ is used (Refs.10,11).

$$T_w(t) - T_w(0) = 2q\sqrt{t}/\sqrt{(\pi\beta)} = R_{dyn}\,q \qquad (4)$$

where the dynamical thermal resistance of the wall R_{dyn} is zero at t=0, increasing as the square root of time.

While in the derivation of Equation 4, q is required to be constant, q varies in general with time. The complete solution of the diffusion heat equation is an integral over the time history of q(t), and the approximation is acceptable when the actual value of q(t) is close to its time averaged value.

Equation 4 has been used for example, to measure β in situations where the room wall materials are not known, or when the walls are not all made out of the same material. To this effect it is sufficient to heat the closed room with an electrical fan heater and to plot the measured air temperature as a function of time (Ref.11).

Coupled ventilation and thermal modelling. After combining Equations 1-4 one solves the final non-linear expression for T_{in}. A few iterations are sufficient for each value of t.

There are two new parameters in the model.

(i) the product $C_2S_i.h$ in Equation 3, which concerns the rapid drop in temperature after t=0. While the uncertainty in the total wall surface area S_i can be made small and the error in h is about 20%, the parameter C_2 can vary by a factor of two or more and when not known dominates in an error analysis.

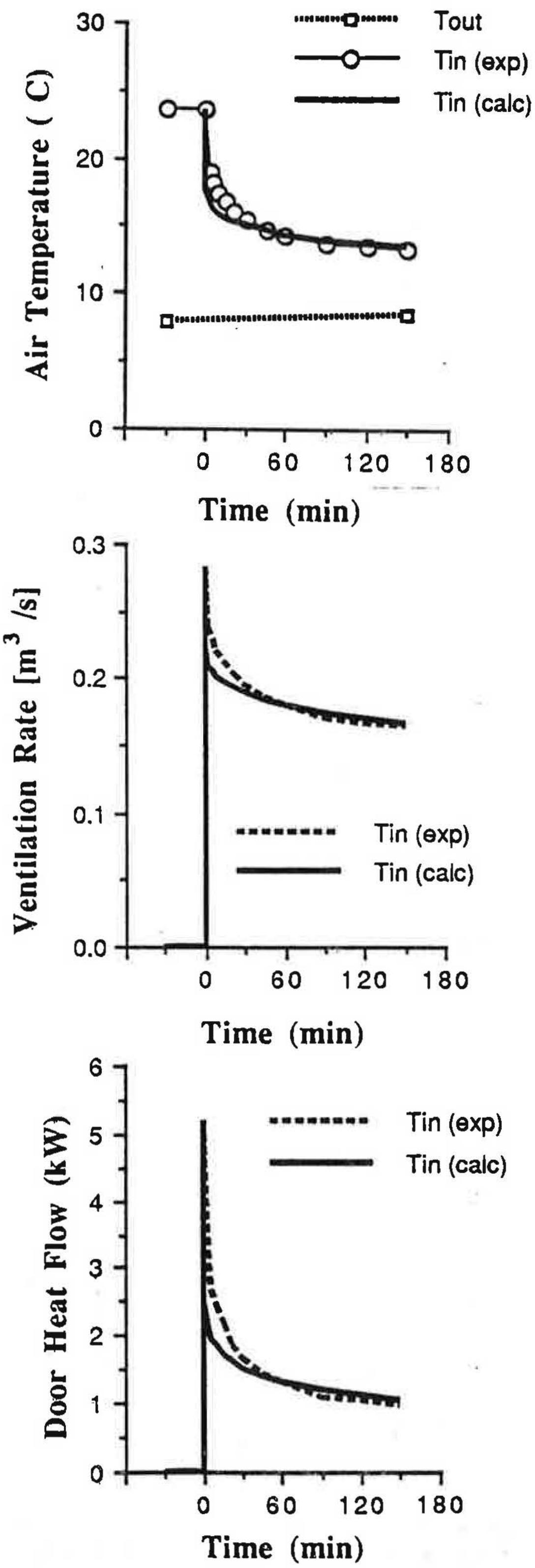

Figure 5: Effect of the opening of the door (0.7 x 2m^2) of a well insulated cabin (2.1 x 2.6 x 6.5 m^3). a) Measured T_{in} as a function of time compared with the model. The coefficient $C_2 = 1$ and there are no free parameters. Ventilation b) and heat loss rates c) after opening the door are calculated from the values of T_{in} in Figure 5a with the help of Equations 1 and 2.

Acknowledgements

This research was sponsored by the Swiss Federal Energy Office (OFEN).

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