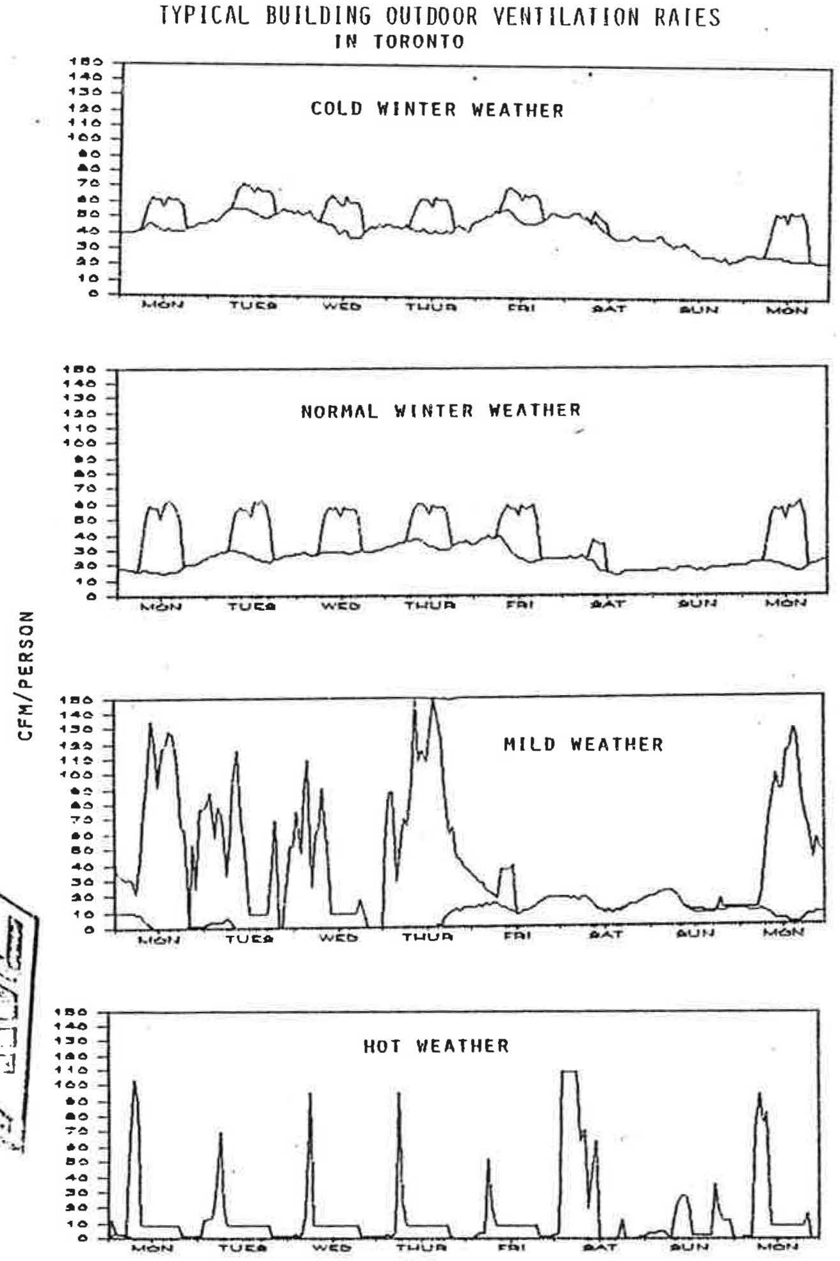

FIGURE 4

TRANSIENT MODELLING OF INDOOR AIR QUALITY

G.D. McIntosh, G.H. Bragg, and D.L. Siurna
Department of Mechanical Engineering
University of Waterloo
Waterloo, Ontario

Abstract

A simple model of the dynamic behaviour of air flows in buildings is proposed and its effect upon the relationship between transient infiltration and the concentration of contaminants inside the building envelope is determined. The model suggests that the time scale of the building dynamic behaviour is an order of magnitude smaller than the time scales of infiltration due to wind and mechanical ventilation effects, enabling the building air flow dynamics to be decoupled from the infiltration and ventilation effects.

Introduction

Traditional descriptions of indoor air quality have frequently been based upon attempts to use steady-state models to describe time averaged quantities. Recently, however, Sandberg (1981, 1983), Skaret and Mathisen (1983) and others have attempted to provide broader definitions of both ventilation effectiveness and concentration parameters which provide useful statistical descriptions of indoor air quality. This work has in the main been adapted from models based on continuous flow analysis of chemical systems. With the aid of this vocabulary, it is possible to begin to develop models of indoor air behaviour which describe the time varying properties found in practice. In addition to the above models, the industrial environment provides extensive data on the time variability of contaminants quality is not yet available in the residential environment.

Two of the most important parameters in the prediction of indoor concentrations of pollutants are the rates of infiltration and mechanical ventilation. If a time varying model of concentration is necessary, then the time varying properties of infiltration and mechanical ventilation are important. Furthermore, the elastic properties of the building can conceivably become important in both the analysis of infiltration and indoor concentration. It is the object of this paper to attempt to model response characteristics of a structure and enclosed air mass in a preliminary way to determine their influence on infiltration and ventilation and hence upon indoor concentration of contaminants. The results are intended for use in the construction of a stochastic model of infiltration which is presently under development. The procedure will be to first consider the effect on the dynamic response of the air mass inside the building of building elasticity and to determine typical pressure wave travel times inside buildings. A model of the dynamic behaviour of the interior air mass is then developed, and the resulting time varying concentration is predicted.

The problem of unsteady modelling of ventilation has been considered by several authors. Katayama (1983) has recently developed a probabilistic model relating ventilation rates and indoor concentrations but has not considered instantaneous dynamic models in detail. Hill and Kusuda (1975) considered experimentally the relationship between fluctuating wind speeds and pressure differences on building envelopes and the resulting infiltration rates. They did not consider the dynamic properties of the enclosure directly but did conclude that the major discrepancies between actual flow rates and those determined by steady state analysis were due to simultaneous forward and reverse flow through windows. In addition Hill and Kusuda obtained power spectra for wind velocity components (Fig. 1) and pressure differentials (Fig. 2) across windows for a typical application. In this case, they found the highest energy containing frequencies were of the order of 0.1 Hz or less.

In the case of mechanical ventilation, the transient aspects are dominated by the startup and shutdown processes since the normal operation of ventilation systems does not provide for varying flow rates. The exceptions to this are mainly in the residential building area. In most cases, industrial fans have starting and stopping times of the order of 1-5 seconds or 0.2-1 Hz.

The Time Scale of Building Air Mass Response

In order to concentrate upon the effect of the building properties upon the air mass dynamics, we shall assume simple models of both infiltration and internal mixing. Infiltration can occur due to a steady inflow-outflow combination and by time-varying pulsations. Inside the building, mixing will occur and for simplicity we have assumed total mixing or uniform concentration. This corresponds to the single zone model of Sandberg. Such a simplification is not realistic in the present context but, as will be seen, it will act to accentuate any effects due to building elasticity.

The fluid capacitance, inertance and wave travel time are determined for a rigid building as

Capacitance $C_f = \frac{}{\rho a^2}$

$$\text{Inertance } I_f = \frac{\rho L}{A} \tag{2}$$

$$\text{Wave travel time } t' = \sqrt{I_f \cdot C_f} = L/a \tag{3}$$

where: L is a characteristic building length (in this case in direction of imposed pressure difference and flow);
A is the building cross section normal to L;
ρ is fluid density;
and a is the acoustic velocity.

The acoustic velocity in a non-rigid building may be estimated (Streeter and Wylie, 1975) by

$$a' = \frac{a}{1 + \frac{KD}{Eh}} \tag{4}$$

where: a is the acoustic velocity in a rigid container;
K is the bulk modulus of elasticity of air;
D is a representative diameter of the building normal to the net flow in the structure;
E is the Young's modulus of the building envelope;
and h is a representative thickness of the building envelope.

For a typical industrial structure we may set $a = 350$ m/s, $K = 100$ KPa, $E = 10^7$ kPa, $D = 30$ m, $h = 0.1$ m, $L = 30$ m and height of 10 m.

Then
$a' = 0.997a$
$C_f = 0.0306\ m^5/N$
$I_f = 0.24\ N\ s^2/m^5$
$t' = 0.086$ seconds

As is clear from these values, the acoustic velocity is unlikely to be dramatically altered by a normally compliant building and only special cases such as inflatable structures are likely to have time constants sufficiently large to be important.

These calculations show that the time constants and air mass natural frequencies of relatively large structures are such that responses are very fast compared to the time scales of pressure and wind variation reported by Hill and Kusuda.

The possibility of infiltration being affected through a sudden imposition of a uniform externally applied increase or decrease of pressure is also small. A uniformly applied increase in pressure of 10 Pa related to a wind pressure from a 4 m/s wind would increase the internal air mass by less than 0.01%. We conclude that even with a reasonably compliant structure, the time for the air mass of a structure to respond is significantly less than the time scales typical of external wind forces.

The effect of air inertia on unsteady flows and concentrations requires a more detailed analysis. In particular, it is necessary to develop the unsteady flow equations and apply the resultant model as an input to the unsteady concentration equation.

The unsteady flow of air in a building accounting for inertial effects can be described by Euler's equation of motion in the unsteady, turbulent resistance form (Streeter and Wylie, 1975).

$$\frac{1}{\rho}\frac{\partial P}{\partial s} + g\frac{\partial z}{\partial s} + V\frac{\partial V}{\partial s} + \frac{\partial V}{\partial t} + \frac{KV^2}{2L} = 0 \qquad (5)$$

where: P = pressure
g = acceleration due to gravity
V = velocity
t = time
K = loss coefficient
D = diameter
z = elevation
s = elemental length
L = total length of the structure in the direction of the applied pressure difference

The loss term is expressed in terms of a loss coefficient related to the building length and the internal velocity. The relationship to the internal velocity is reasonable but a direct relation to building length is only acceptable if a value of K is chosen to give a realistic value of air changes per hour. That is, an assumption for steady state air changes enables K to be evaluated. Integrating equation (5) over the entire length of the building assuming uniform acceleration of the air mass within the building (as justified in the previous section) and neglecting changes in elevation, the following equation is obtained:

$$\frac{dV}{dt} + \frac{K}{2L}V^2 = \frac{\Delta P}{\rho L} \qquad (6)$$

where, ΔP is the pressure differential across the building. The simplest case to consider is that of a sudden imposition of a pressure difference in the direction L across the building. Using the condition that the initial internal velocity is zero, an expression for velocity as a function of time is obtained by integrating equation (6) with respect to time. Then

$$V_{(t)} = \sqrt{C_2/C_1}\,\frac{e^{2\sqrt{C_1C_2}\;t}-1}{e^{2\sqrt{C_1C_2}\;t}+1} \qquad (7)$$

where, $C_1 = K/2L$
$C_2 = \Delta P/\rho L$

The steady-state velocity is equal to $\sqrt{C_2/C_1}$. Equation (7) will be used to describe the transient air flow due to infiltration as a result of a sudden wind gust. The model assumes a constant value for wind pressure. Equation (6) determines that the steady-state velocity-pressure relationship is of the form:

$$V \propto \Delta P^n$$

where $n = 1/2$. Hill and Kusuda (1975) and others have indicated that the experimental value for the exponent n may actually vary between 1/2 and 1. However, the general characteristics of the flow may be determined with n set at 0.5.

Contaminant Concentration Model

Several models have been developed which describe the concentration of a contaminant in a building. For the purpose of this paper a simple, one zone model which assumes complete mixing is presented (Sandberg, 1981). The concentration is considered to be the same at every point and is described by

$$V_T\frac{dC}{dt} = -QC + \dot{m} \qquad (8)$$

where, C = concentration
Q = volume flow rate of air
V_T = total volume of building
$\dot{m}$ = contaminant generation rate

The effect of transient flow on contaminant concentration may be obtained by substitution of (7) into (8) so that:

$$\frac{dC}{dt} = -\frac{A}{V_T}\sqrt{C_2/C_1}\,\frac{e^{2\sqrt{C_1C_2}\;t}-1}{e^{2\sqrt{C_1C_2}\;t}+1}\,C + \dot{m} \qquad (9)$$

In order to solve the concentration model, equation (9), it was necessary to use a numerical solution procedure. Since the equation is a first order ordinary differential equation, it can be solved accurately using a fourth order Runge-Kutta procedure (Hornbeck, 1975).

Figures 3 to 6 are plots of transient flows, based on equation (7). The data presented are for various building geometries, pressure differentials and infiltration rates expressed as air changes per hour (ACPH). Q_{ss} is the steady state flow rate achieved at $t = \infty$, C_{ss} is the steady state concentration at $t = \infty$ for a source strength m_2. Some obvious trends are indicated by the data. Those buildings with low infiltration rates, and hence tighter construction, allow the flow to reach steady state noticeably faster than those with high infiltration rates. Also, the time to reach steady state is seen to increase with decreasing pressure differential.

The most significant difference in the time to reach steady state is related to building geometry. The time to reach steady state for the building with a length of 30 m was 1 second or less, but with a length of 100 m this time is increased by a factor of approximately 10. Transient flows all achieve steady state in less than 10 seconds in the cases considered.

To best illustrate the effect of transient infiltration flow on concentration, a situation where the transient nature of the flow is significant (see Fig. 5) was studied. A building, 100 m in length with a cross-sectional area of 100 m^2, was considered. In Figure 7 the result of imposing an instantaneous pressure differential and contaminate source ($\dot{m}_2$ = const for $t>0$, $\dot{m}_1$ = const for $t \leq 0$ where $\dot{m}_1$ is the contaminant source flux before the pressure increment and $\dot{m}_2 > \dot{m}_1$ is the source flux after the pressure increment) on a background concentration is plotted. In Figure 8 the case of a sudden increase in external pressure on a decaying concentration ($\dot{m}_2 = 0$ for $t>0$) is plotted. The steady flow and transient flow cases are plotted in both figures. Any differences between the simple model of concentration buildup and the model accounting for air acceleration are seen to be small before 10 seconds and have no effect over longer periods.

The data presented are based on an infiltration rate of 10 air changes per hour. This value is approaching an upper limit in terms of realistic infiltration rates. Even so, the transient effects due to considering air mass acceleration and building elasticity on contaminant concentration are minimal.

Conclusions

1. The wave travel time of a pressure pulse in building enclosures is very short compared to both the characteristic time scales of wind fluctuation and mechanical ventilation starting and stopping times.
2. The time scale for inertial effects in air in typical enclosures is so small that instantaneous behaviour at the time scale of pressure variation and ventilation variation may be assumed.
3. It is expected that alterations in the assumptions of the model will not significantly affect the conclusions. Specifically, it is not likely that the exponent of pressure in the pressure-flow relationship, incomplete mixing, combinations of ventilation and infiltration, or the non-additive effects of pressure differentials, will substantially alter the above conclusions.
4. The time scales of infiltration and mechanical ventilation are one order of magnitude larger than the time scales of the building air mass response. Hence the building will provide an "instantaneous" response to unsteady infiltration and ventilation processes.
5. The unsteady response characteristics of the internal building air mass are unlikely to be of importance in normal modelling of the infiltration-ventilation-air contamination system. However, studies of ventilation of combustion product or radiation product venting which require very fast system response may need to consider this aspect of the problem.

References

Ayer, H. and Burg, J. (1973) Time Weighted Averages vs Maximum Personal Sample. Presented at the Am. Industrial Hygiene Conference, Boston.

Hill, J.E. and Kusuda, T. (1975) Dynamic Characteristics of Air Infiltration, ASHRAE Transactions, Vol. 81, pp. 168-184.

Hornbeck, R.W. (1975) Numerical Methods, Prentice-Hall.

Katayama, T. (1984) A Study of a Probabilistic Model of Wind Induced Ventilation, Wind Engineering 1983, Elsevier.

OSHA (1979) Office of Safety and Health Administration, Industrial Hygiene Field Operations Manual.

Sandberg, M. (1981) What is Ventilation Efficiency?, Building and Environment, Vol. 16, #2, pp. 123-135.

Sandberg, M. (1983) Ventilation Efficiency as a Guide to Design, ASHRAE Transactions, Vol. 89, pp. 455-479.

Skaret, E. and Mathisen, H.M. (1983) Ventilation Efficiency--A Guide to Efficient Ventilation, ASHRAE Transactions, Vol. 16, pp. 480-495.

Streeter, V.L. (1961) Handbook of Fluid Dynamics, McGraw-Hill.

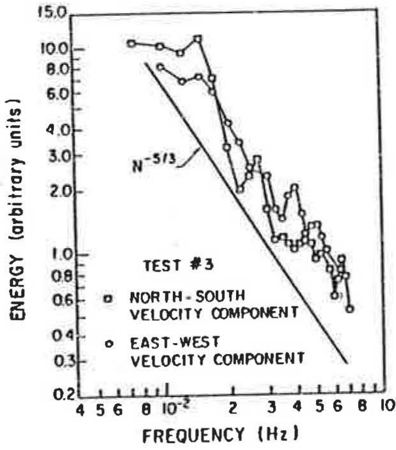

Fig. 1 Power spectrum for wind velocity components after Hill and Kusuda, 1975

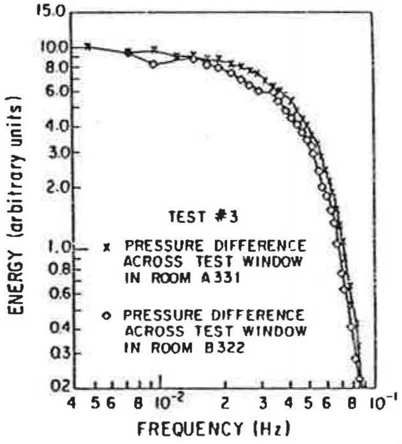

Fig. 2 Power spectrum for pressure differentials after Hill and Kusuda, 1975

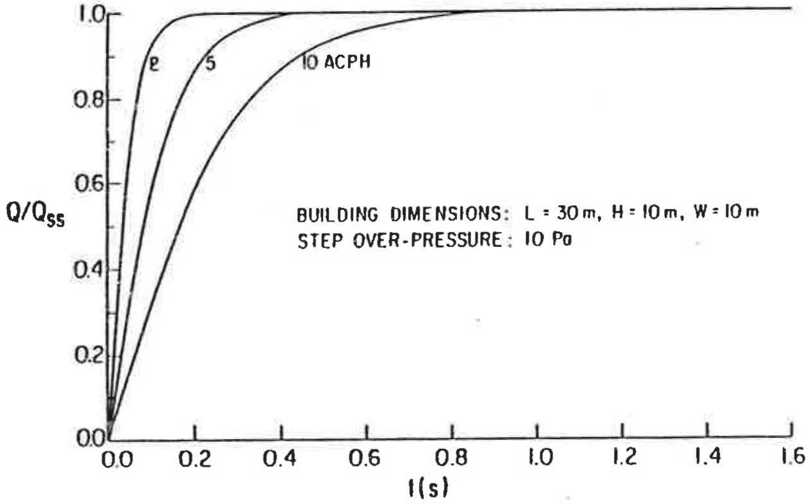

Fig. 3 Transient flow behaviour - Pressure differential of 10 Pa.

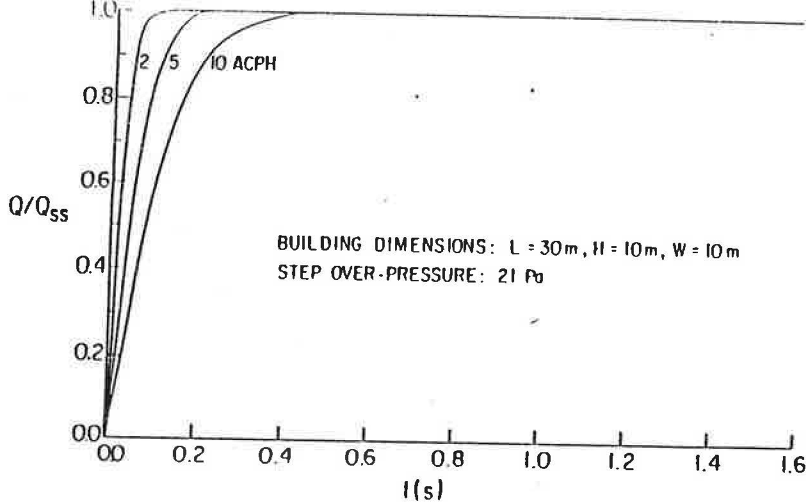

Fig. 4 Transient flow behaviour - Pressure differential of 21 Pa.

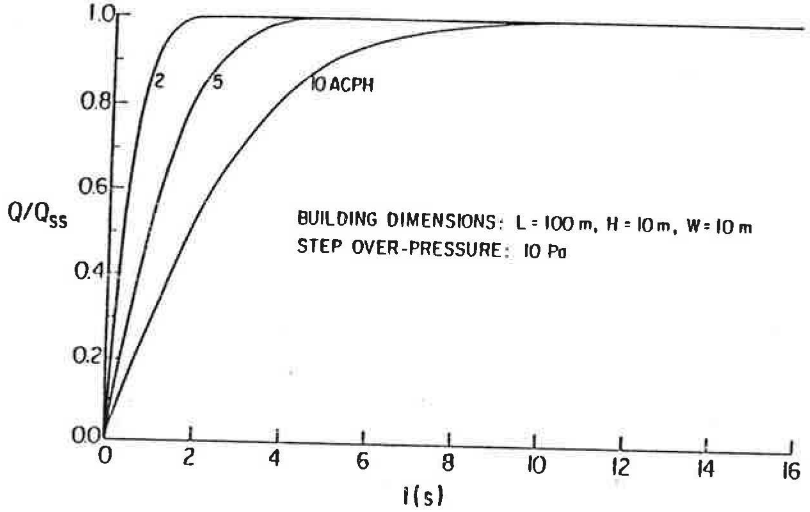

Fig. 5 Long building, low pressure differential. Transient flow behaviour.

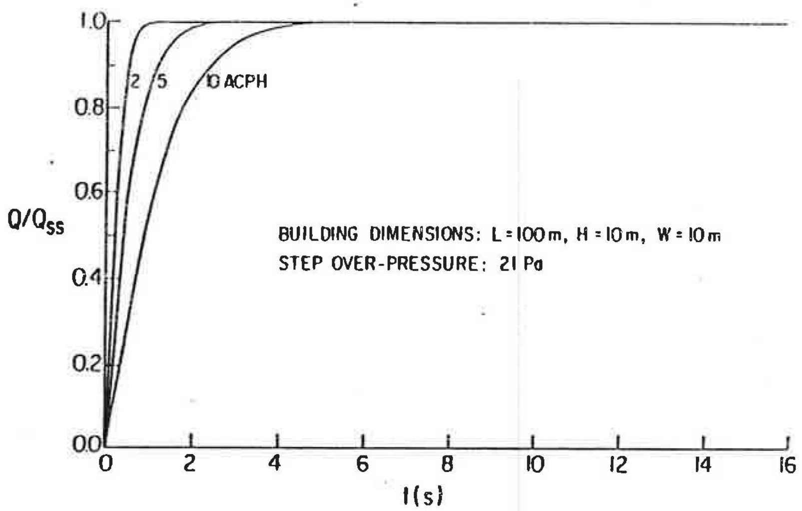

Fig. 6 Long building, high pressure differential. Transient flow behaviour.

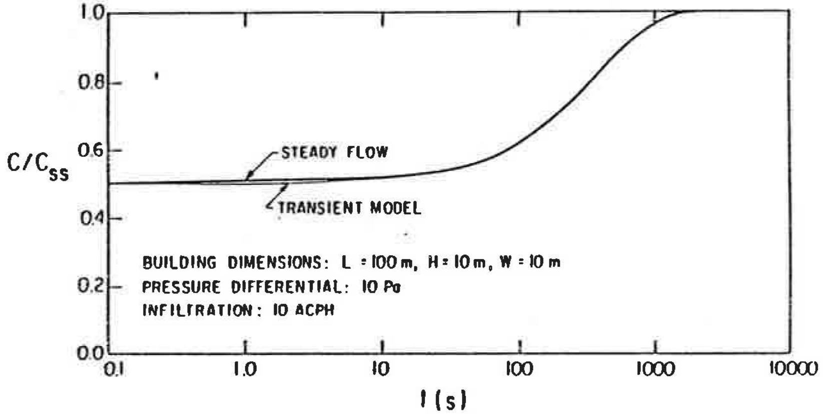

Fig. 7 Effect on concentration of a suddenly imposed concentration flux and pressure differential.

$\dot{m}_2$ = constant ($t > 0$) $\dot{m}_1$ = constant ($t \leq 0$)

Figure 3.3.b shows computed and experimental thermal effects of forced convection through continuous insulation in a corner structure. Pressure difference between air space on both sides of the wall corner (ΔP_a) and the material properties of insulating materials for calculation were taken corresponding to test house conditions and materials. Agreement between computed and measured results seems to be satisfactory. Corner structure without vertical wood frame (in fig 3.3.b) was also computed and according to results the frame decreases convective heat loss considerably.

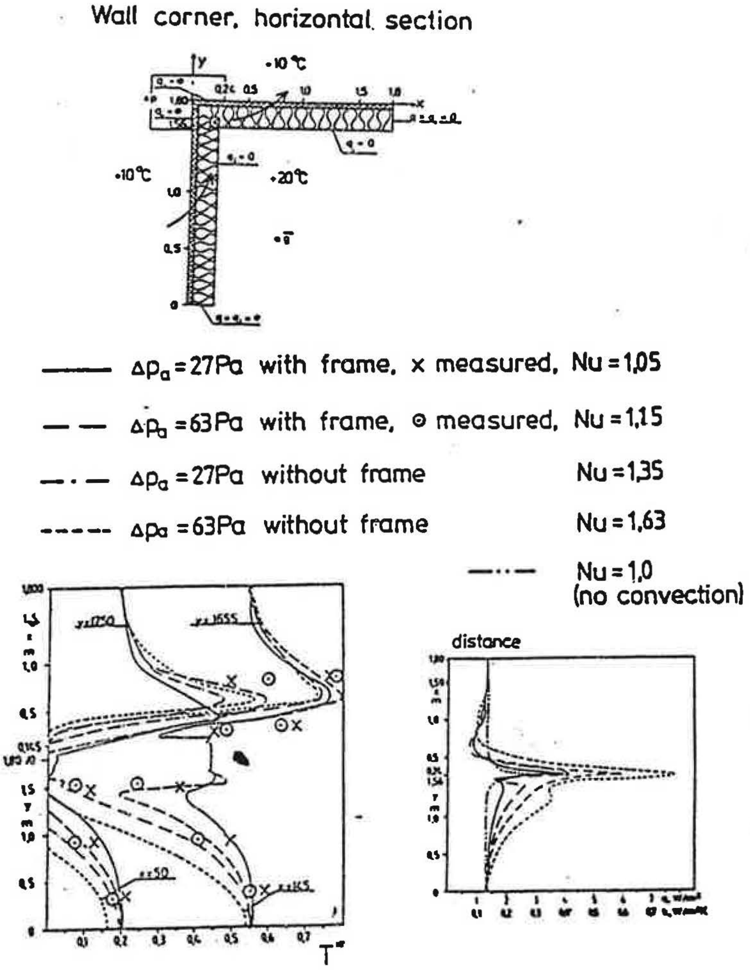

Figure 3.3.b. Computed and experimental distributions of temperature and heat flow density in a wall corner with mineralwool windbreak, continuous insulation and forced convection through it in corner. Temperature are given at depths 145 mm and 50 mm from cold surface of windbreak (total thicnes 50 mm + 190 mm) and heat flow density at inner surface.

REFERENCES

Kohonen, R., Kokko, E., Mähönen, T., Natural and forced convection in mineral fibre wall insulation (in Finnish). Technical Research Centre of Finland, Research Reports 431, Espoo 1986, 119 p.

Karvonen, M-L., Virtanen, M., Sructural methods for damping of winds pressure effects on the supply air intake of mechanical exhaust ventilation system. Technical Research Centre of Finland, not published.