EFFECTIVE VENTILATION

9th AIVC Conference, Gent, Belgium
12-15 September, 1988

Paper 15

AIR INFILTRATION INDUCED BY HEATING APPLIANCES

GIAN VINCENZO FRACASTORO (1), MARCO MASOERO (2)

(1) Università della Basilicata, Via Nazario Sauro 85
85100 POTENZA (Italy)

(2) Politecnico di Torino, Corso Duca degli Abruzzi 24
10129 TORINO (Italy)

SYNOPSIS

Infiltration heat losses due to heating appliances located within the living space are normally evaluated by reducing the conversion efficiency of the boiler, with no consideration for the fluid dynamic interaction between boiler, chimney and building. Purpose of this work is to develop a simplified mathematical model of the overall (building + boiler + chimney) system, suitable to calculate the pressure distribution and air flow rate in the building induced by the simultaneous effect of natural forces and the exhaust system.

Inside pressure and air flows across the envelope, through the boiler, the draft diverter, and the stack are calculated by means of a steady-state model.

Results are presented as a parametric analysis which points out the dependence of air infiltration rates on factors such as envelope permeability and weather conditions, and the dependence of stack flow rate on weather parameters.

LIST OF SYMBOLS

A = area of envelope component (m^2)
ACH = air changes per hour (h)-1
Ast = ratio between stoichiometric air and fuel mass flow rates
c = flue gases speed in the stack (m/s)
C = permeability coefficient (m3/(h·m^2·Pa^n))
Cp = wind pressure coefficient
d = atmospheric boundary layer thickness (m)
g = gravity acceleration, equal to 9.81 m/s^2
h = reference height
hu = useful height of the stack (m)
Hi = lower heating value of fuel (kJ/kg)
k = internal air flow resistance
m = mass flow rate (kg/s)
n = infiltration flow exponent
P = air pressure (Pa)
Pi = boiler infiltration loss
Q = volume air flow (m3/s)
R = excess air
Sr = ratio between mass flow rate in the stack and in the flue
T = absolute temperature (K)
t = time (s)
v = wind speed (m/s)
V = building volume (mc)
z = height (m)
β = boundary layer exponent
β^* = equivalent flow friction coefficient in the stack
δ = specific mass of air (kg/mc)

Indices

b = in the boiler/flue
e = external, building
f = fuel
i = indoor
in = incoming
out = outgoing
pn = neutral level
s = in the stack
w = at the weather station

1. INTRODUCTION

The study of air infiltration induced by heating appliances is one of the typical "second approximation" problems which have been recently investigated, following the great impulse of research in the building physics area during the last decade. It is, nonetheless, a problem which deserves some attention, due to the increasing number of individual heating systems being installed within the living spaces, and to the growing interest in the areas of ventilation and indoor air quality.

A thorough analysis of the problem requires a model capable of taking into account simultaneously the air infiltration induced by natural forces and the behaviour of the boiler plus exhaust system.

Calculation procedures and standards for the design of chimneys have been developed since a long time in several countries, e.g., by CSTB in France /1/ and by DIN in Germany /2/. Recent research work in the field focuses on experimental testing (see for example Anglesio et al. /3/), and on the dynamic behaviour of branched chimneys (Andreini et al., /4/).

The problem of evaluating the use of indoor air as combustion air in terms of boiler infiltration losses was first analysed by Chi and Kelly /5/, and Kelly et al. /6/.

The thermal performance of open fireplaces was investigated from the experimental and theoretical point of view by Modera and Sonderegger /7/. An experimental analysis of the interactions between a chimney and a building under the effect of external forces (wind, temperature difference) was presented by Shaw and Brown /8/. Further theoretical and experimental work was done by Shaw and Kim /9/.

This paper analyses the interaction between air infiltration and the boiler plus exhaust system using a simplified model, suitable for analysing the sensitivity of the phenomenon to a number of parameters, such as wind speed, air temperature, building permeability, etc.

A large fraction of the individual boilers located indoors, except the so-called "balanced draft systems", make use of indoor air for combustion. Moreover, the use of draft diverters -- which causes an extra infiltration rate -- is becoming more and more common for their ability to decrease the flue gas dew point, and for safety reasons, because in case of reverse flow they prevent the extinction of the combustion flame by the flue gases.

In central systems draft regulators are used, which are able to decrease the chimney draft to the point where draft is balanced by flow resistances, thus allowing a better matching between boiler and chimney even when the stack is oversized. Moreover, as pointed out by Kunz /10/, such devices allow, in the off-period of the burner, the ventilation of the stack and therefore the evaporation of condensate.

2. MATHEMATICAL MODEL

2.1 Air infiltration across the envelope

The model adopted is described in detail in a previous paper by Fracastoro and Pagani /11/, where it was used to derive a simplified procedure to calculate natural air infiltration in buildings.

The building envelope is subdivided into a number of elementary areas of variable height and width equal to the width of the façade and the pressure difference is calculated across each area. Then, assuming the air permeability of each elementary area is known, the air flow rate is calculated and summed up over the whole envelope. The condition that the incoming air flow rate is equal to the outgoing flow rate allows to determine the internal pressure.

The model does not take into account turbulence-induced ventilation, and the lower floor and upper ceiling are supposed to be perfectly airtight.

The external pressure on the façade is calculated by the following formula

$$Pe(x,y,z) = Pe(h) - \delta e \cdot g \cdot (z-h) + Cp \cdot \delta e \cdot v^2/2 \qquad (1)$$

where the pressure coefficients Cp are those indicated by Wise /12/, assumed constant over the entire façade. The wind velocity varies with height according to the law proposed by Shaw and Tamura, /13/:

$$v(z) = vw*\left(\frac{dw}{zw}\right)^{\beta w} * \left(\frac{z}{de}\right)^{\beta e} \qquad (2)$$

The atmospheric boundary layer thickness and exponent are given in Tab. 1, as a function of the type of terrain surrounding the building. In this analysis the wind velocity is assumed to be known at the building site, 10 m above the ground.

TAB. 1 - BOUNDARY LAYER THICKNESS AND EXPONENT

Surrounding terrain	d(m)	ß
urban centre	520	0.400
suburbs or rough countryside	400	0.286
countryside	280	0.143

The internal pressure is considered to be a function only of the height above ground, and is given by:

$$Pi(z) = Pi(h) - \delta i \cdot g \cdot (z-h) - \Sigma(k \cdot \Delta Px) \qquad (3)$$

where the sum is extended to all floor partitions below the considered level z, k is the so-called "internal air flow resistance" /11/, and ΔPx is the maximum pressure drop across the floors, given by

$$\Delta Px = -g \cdot hi \cdot (\delta e - \delta i) \qquad (4)$$

The value of k varies between 0, for buildings having an element (as the stairs or lift well) providing good vertical continuity, and 1 for buildings made of superimposed, vertically tight floors.

Assuming a reference height equal to the unknown neutral level height h = zpn, the pressure difference between outdoor and indoor is given by:

$$\Delta P(x,y,z) = Pe(x,y,z) - Pi(z) =$$

$$= g \cdot (\delta i - \delta e) \cdot (z - zpn) + Cp \cdot \delta e \cdot v^2/2 + \Sigma\ k \cdot \Delta Px \qquad (5)$$

The incoming air flow rate is:

$$Qin = \int_{A+} C(x,y,z) \cdot |\Delta P(x,y,z)|^n \cdot dA \qquad (6')$$

where the integral is extended to the area A+ across which ΔP is positive and

$$Qout = \int_{A-} C(x,y,z) \cdot |\Delta P(x,y,z)|^n \cdot dA \qquad (6")$$

extended to the area A- across which ΔP is negative.

By imposing the continuity equation

$$Q = Qin = Qs + Qout \qquad (7)$$

where Qs is the volume air flow exfiltrating through the stack, calculated as shown in the next sections, the neutral level height zpn is determined, together with the corresponding value of Q, or $ACH = 3600 \cdot Q/V$.

2.2 Boiler and exhaust system characteristics

A typical hot water individual heating system consists of a gas-fired boiler coupled to the exhaust system, including the flue, the draft diverter and the stack. The draft diverter connects the stack with the ambient in which the boiler is located. The flue and the stack are respectively the portions of the exhaust system upstream and downstream of the draft diverter. Hence, the chimney and the boiler are actually uncoupled from the fluid dynamics standpoint.

During the boiler on-period the flue gas mass flow rate in the boiler and flue may be considered constant, both for natural draft and forced draft boilers. The equation relating the flue gas mass flow rate mb to the fuel mass flow rate mf, the stoichiometric air Ast, and the excess air R is:

$$mb = mf \cdot (1 + R \cdot Ast) \qquad (8)$$

During the boiler off-period the air flow rate is no longer constant, being determined by the mechanical equilibrium between the available pressure drop across the stack and the friction pressure loss. The available pressure drop depends in turn on the temperature of the air in the stack, which varies with time. In order to determine the air flow during the off-period, the temperature transient in the chimney plus boiler system should therefore be analysed; such aspect is not yet implemented in the model presented in this paper.

When a draft diverter is adopted, if the gas flow rate corresponding to the gas temperature in the stack is higher than the flow rate in the boiler, an extra flow of air (at ambient temperature) is drawn into the stack through the draft diverter. The dilution of the flue gases with ambient air lowers the average gas temperature in the stack, therefore reducing the stack draft until a different equilibrium condition is reached. The ratio of the mass flow rate in the stack to the mass flow rate in the flue is defined as:

$$Sr = ms \,/\, mb \qquad (9)$$

Hence, the volumetric flow rate exfiltrating through the stack is:

$$Qs = Sr \cdot mb / \delta i \qquad (10)$$

The value of Sr depends on the construction features of the boiler and chimney and on the flue gas temperature. Sr is also influenced by the actual internal pressure value, which in turn depends on the external pressure field described by Eq. (1).

Typical values of Sr for individual gas boilers commonly adopted in Italy range between 2 and 2.5.

In order to compare different boilers it may be useful to express the infiltration heat loss induced by the boiler in terms of boiler losses, i.e., as a fraction of the available heat of combustion. The "boiler infiltration loss" is given by the following expression:

$$Pi = \frac{\int_0^t ms \cdot cp \cdot (Ti - Te) \cdot dt}{\int_0^t ms \cdot Hi \cdot dt} \qquad (11)$$

where the two integrals are extended over time t, comprehensive of an integer number of on-off cycles.

2.3 Pressure and temperature distribution

In this section the calculation of pressures, temperatures and gas flow rates in the boiler, flue, draft diverter and stack is presented.

Basically two different situations may occur with respect to the pressure distribution, i.e.:

i) the natural draft boiler in which the slight underpressure of the combustion chamber (with respect to ambient) determines the flow of combustion air;
ii) the forced draft boiler, in which the burner is equipped with a fan controlling the combustion air flow.

The outdoor pressure Pe(zb) at the boiler level (z = zb) in the undisturbed zone is assumed as the reference value in the pressure calculation. It is also assumed that the flue gas pressure at the chimney outlet (elevation $z = zb + hu$) equals the outdoor air pressure at the same elevation $Pe(zb + hu)$. This fact implies that the discharge gas pressure is not influenced by the local wind speed. Two alternative paths may be followed to determine the pressure drop

$$\Delta Pe = Pe(zb) - Pe(zb + hu)$$

Following the external path, this is equal to the hydrostatic drop

$$\Delta Pe = \Delta Phyd,e = \delta e \cdot g \cdot hu \qquad (12)$$

Alternatively, Δ Pe may be calculated along the path "outside-inside-stack base-stack outlet".

The difference between the reference pressure and indoor pressure $Pi(zb)$ at the boiler level is indicated as:

$$\Delta Pa = Pe(zb) - Pi(zb) \qquad (13)$$

The difference between the indoor pressure $Pi(zb)$ and the pressure at the base of the stack $Pf(zb)$

$$\Delta Pb = Pi(zb) - Pf(zb) \qquad (14)$$

depends on the characteristics of the boiler: for a forced draft boiler ΔPb can be assumed equal to zero, as the pressure losses in the boiler are balanced by the pressure head of the burner's blower, while for a natural draft boiler ΔPb assumes a positive value.

The flue gas pressure difference ΔPf between the stack base and outlet is given by the sum of two terms, i.e.:

i) the "hydrostatic" pressure difference

$$\Delta Phyd,s = \delta s \cdot g \cdot hu \qquad (15)$$

ii) the friction losses

$$\Delta Pw = \beta * \cdot \delta s \cdot c^2 /2 \qquad (16)$$

where the $\beta*$ coefficient includes the effect of both distributed and concentrated flow resistances, as well as the effect of the kinetic term.

Therefore:

$$\Delta Pf = Pf(zb) - Pf(zb + hu) = \delta s \cdot (g \cdot hu + \beta * \cdot c^2 /2) \qquad (17)$$

The following equation may be written by equalizing the two pressure drops

$$\Delta Phyd,e = \Delta Pa + \Delta Pb + \Delta Pw + \Delta Phyd,s \qquad (18)$$

In the latter equation, the known terms are ΔPhyd,e and, in the case of forced draft boilers, the term ΔPb, which can be taken equal to zero. The unknown terms are Δ Pa, Δ Pw and ΔPhyd,s; the two latter terms are a function of the gas speed c and density δs, given that the chimney constructive and geometric characteristics are assigned; the gas density δs is in turn a function of temperature Ts.

Applying the continuity and the energy equations to the draft diverter, and assuming that air and flue gases have equal specific heat, it is found that:

$$mb \cdot Tb + (ms - mb) \cdot Ti = ms \cdot Ts \tag{19}$$

As a first approximation, if the thermal losses of the flue gas are neglected, the temperature Ts also represents the average value in the stack.

2.4 Overall analysis

The overall solution of the problem is obtained with the following procedure:

i. As an initial guess it is assumed Ts = Tb
ii. The neutral plane elevation is initially taken at the mid height of the building; this is equivalent to imposing an initial value of ΔPa.
iii. The gas speed c is calculated from equation (18) and the mass flow rate ms is determined from the continuity equation.
iv. The new value of temperature Ts is calculated from equation (19) and the process is repeated from point iii. onwards until convergence is attained.
v. A check is made on the building air flows, until the continuity equation (7) is satisfied. Otherwise, the position of the neutral plane is modified, i.e. the elevation is moved upwards if Qin < (Qout+Qs) and viceversa, and the calculation is repeated from point ii. until convergence.

Results may be presented in terms of the ratio between the number of air changes with and without chimney:

$$\frac{ACH(w\ chimney)}{ACH(w/o\ chimney)}$$

Alternatively, if emphasys is placed on boiler performance, the boiler infiltration loss Pi may be calculated from the infiltration rate. The relationship between Pi and the number of air changes (ACH) is given by:

$$Pi = \frac{\delta i \cdot V \cdot cp \cdot (Ti-Te) \cdot ACH}{3600 \cdot ms \cdot Hi} \qquad (11)$$

3. CALCULATION HYPOTHESES AND APPLICATION EXAMPLE

In this preliminary phase of the work, a parametric investigation has been performed in order to analyse the sensitivity of the results with respect to some of the most significant parameters (air permeability and weather parameters).

As a first example, a two-storey detached house having a square 12 m x 12 m plan, with a forced draft gas boiler on the ground floor was considered. A constant value of the stack cross section, determined according to standard DIN 4705, was assumed. The characteristic data of the building, boiler and exhaust system are summarized in Table 2. Permeability was supposed to be uniform over the entire envelope.

The pressure difference across the building envelope is plotted in Fig. 1 (A = windward façade, C = leeward façade, B = side façades) with (y) and without (n) exhaust system in the living space; wind direction is assumed perpendicular to façades A and C. The exhaust system produces a decrease of the internal pressure, corresponding to an increase of ΔP across all façades.

Two types of analyses have been performed: the first investigating the influence of the exhaust system on the air infiltration rate of the building; the second analysing the influence of weather parameters on the exhaust system operation.

Results of the former analysis are expressed in terms of the ratio of air changes in the building with chimney to air changes in the same building without chimney, as a function of wind speed and outdoor temperature (see Fig. 2), and wind speed and average envelope permeability (see Fig. 3). As it could be expected, the ratio decreases with increasing wind velocity and temperature difference, and becomes practically independent of outdoor temperature for wind speeds exceeding 4 m/s. Also, the ratio shows a strong dependence on the building permeability, even at high wind speeds.

Results of the latter analysis are shown in Fig. 4, where the variation of factor Sr is reported as a function of wind speed and temperature difference. Sr decreases with increasing wind speed due to wind depressurization of the building; Sr decreases also with decreasing outdoor-indoor temperature differences, due to the reduction of stack draft.

TAB. 2 - CHARACTERISTIC DATA OF BUILDING,
BOILER AND CHIMNEY

indoor temperature	20 °C
boiler heating power	23,490 W
internal air flow resistance	0
flow exponent across building envelope	0.65
fuel type	gas
CO2 percent in flue gases	10 %
chimney loss	12 %
boiler efficiency	80 %
internal diameter of the stack	0.12 m
stack height	5.8 m
ß* coefficient downstream the draft diverter	2.5

4. CONCLUSIONS

The preliminary results of the model agree with a qualitative physical understanding of the phenomena. Obviously, an experimental validation is needed to assess the accuracy of the model.

At the present state the model capability is constrained by a number of simplifying assumptions, the most important of which are:

i. the internal pressure is only dependent on the height above the ground
ii. turbulence induced ventilation is not taken into account
iii. thermal dynamic behaviour of the chimney is not considered, and therefore the boiler is considered to be operating under steady-state conditions
iv. temperature of the flue gases is assumed constant in the stack

However, these limitations should not affect the order of magnitude of the results and the correlation trends with the parameters. For example, the results show that the influence of the exhaust system on the ventilation rate (Figures 2 and 3) is by far more marked than the influence of the weather parameters on the exhaust system operation (Fig. 4).

Research work in this area seems promising, due to the rising interest in indoor air quality, and to the rapidly developing use of individual boiler systems located within the living space and equipped with draft diverters.

Future developments of this research will address the transient behaviour of the system in on-off cycle boiler operation and a more detailed description of the horizontal air flows inside the building.

5. REFERENCES

1. CSTB
"Règles et processus de calcul des cheminées fonctionnant en tirage naturel". Paris, décembre 1975.

2. DIN
Standard n. 4705 Part I and II "Berechnung von Schorsteinabmessungen", 1979.

3. ANGLESIO, P., CARDINALE, N., CARUSO, C.
"Sviluppi della ricerca italiana sulla progettazione e sulle prestazioni energetiche dei camini". La Termotecnica, January 1988.

4. ANDREINI, P.A., BUCCI, G., ROTA, G.
"Aspetti tecnici e normativi del dimensionamento dei camini collettivi ramificati". La Termotecnica, January 1988.

5. CHI, J., KELLY, G.E.
"A method for estimating the seasonal performance of residential gas and oil-fired heating systems". ASHRAE Trans., T-78-1 No. 3, pp.405-421.

6. KELLY, G.E., CHI, J., KUKLEWICZ, M.E.
"Recommended testing and calculating procedures for determining the seasonal performance of residential central furnaces and boilers". National Bureau of Standards, NBSIR 78-1543, 1978, Washington.

7. MODERA, M.P., SONDEREGGER, R.C.
"Determination of in-situ performance of fireplaces". Lawrence Berkeley Laboratory Report LBL-10701. August 1980.

8. SHAW, C.Y. and BROWN, W.C.
"Effect of a gas furnace chimney on the air leakage characteristic of a two-storey detached house" Proceedings 3rd AIC Conference, London, U.K., September 1982, pp. 12.1 - 12.13.

9. SHAW, C.Y. and KIM, A.
"Performance of passive ventilation systems in a two-storey house" Proceedings 5th AIC Conference, Reno, Nevada, USA, pp. 11.1 - 11.27.

10. KUNZ, W.
"Camini per impianti di riscaldamento ad alto rendimento. Aspetti teorici e sperimentali". La Termotecnica, January 1988.

11. FRACASTORO, G.V. e PAGANI, R.
"Un modello sintetico per il calcolo delle infiltrazioni d'aria". La Termotecnica, Febbraio 1988.

12. WISE, A.F.E.
"Ventilation of buildings". Proceedings of Conference Heat Transfer in Buildings, Dubrovnik, 1977.

13. SHAW, C.Y., TAMURA, G.T.
"The calculation of air infiltration rates by wind and stack action for tall buildings". ASHRAE Trans. 1977, Part 2.

ACKNOWLEDGEMENTS

This work has been partially funded by CNR-PFE 2 under a research grant on "Natural and mechanical ventilation in buildings" for 1987.

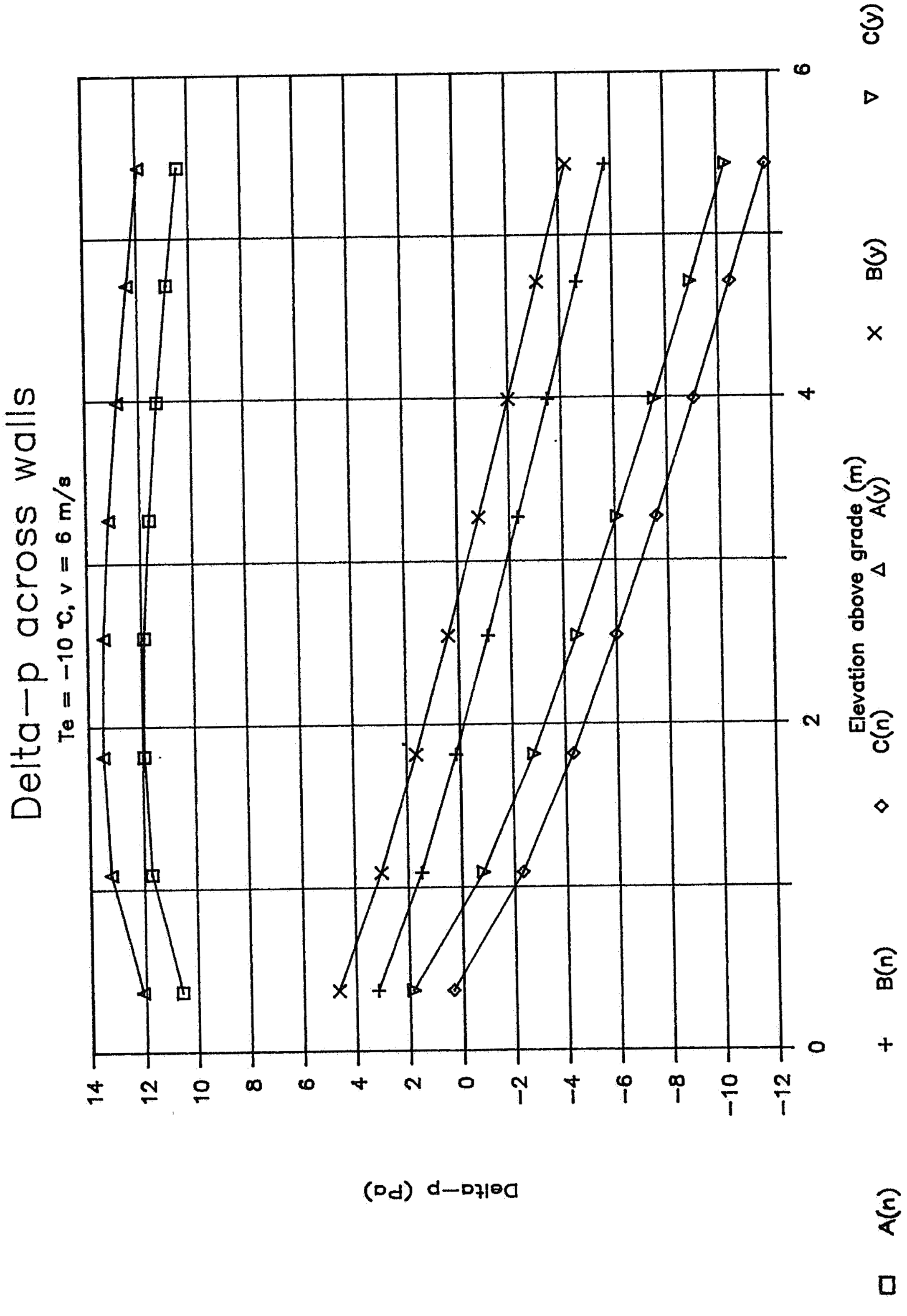

Fig. 1 - Pressure difference across the building façades (A = windward, C = leeward, B = side), for Te = -10°C, v = 6 m/s
(y) = with chimney
(n) = without chimney

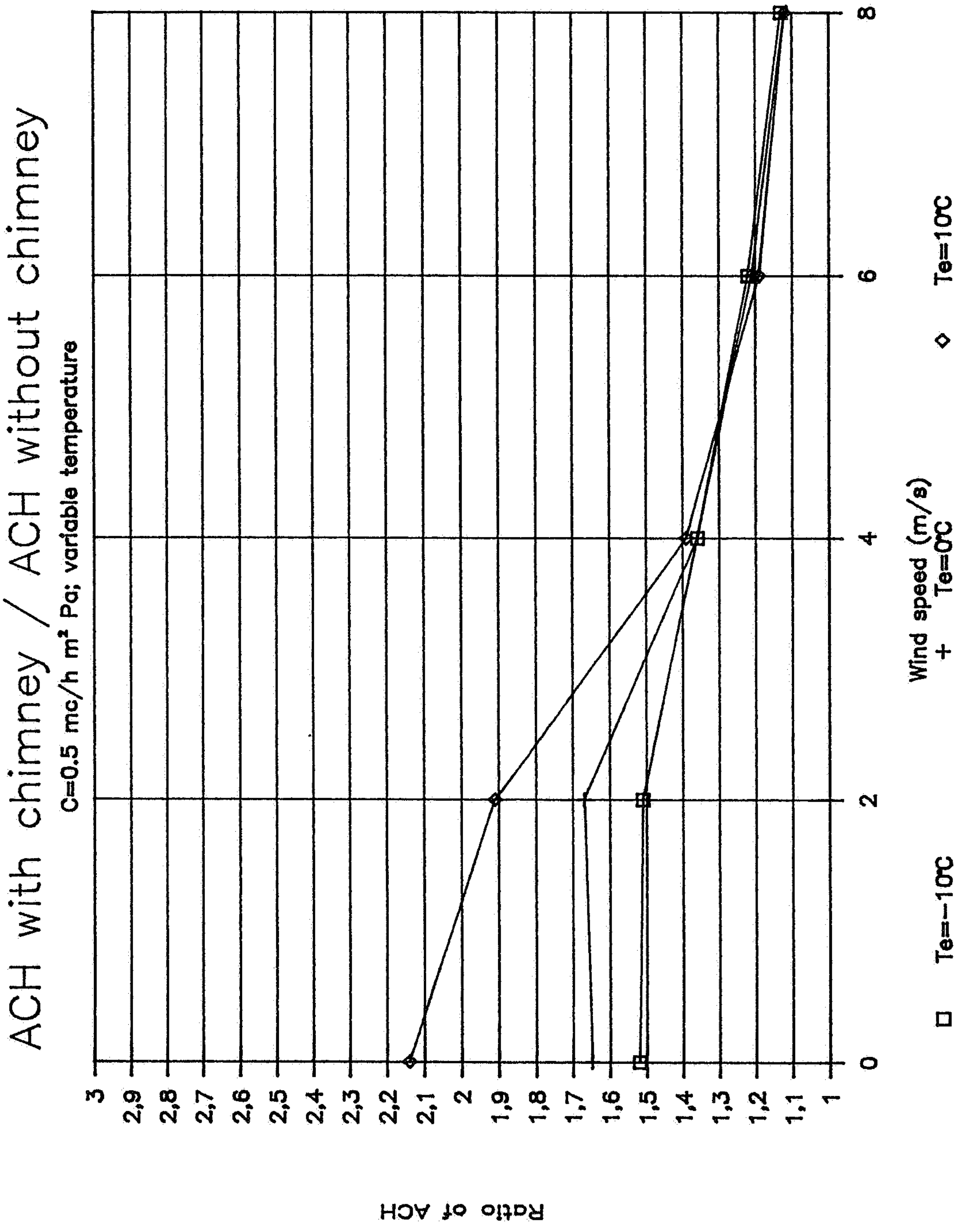

Fig. 2 - Ratio of airchanges with and without chimney as a function of v and Te, for an average permeability C = 0.5 mc/h·m²·Pa^n.

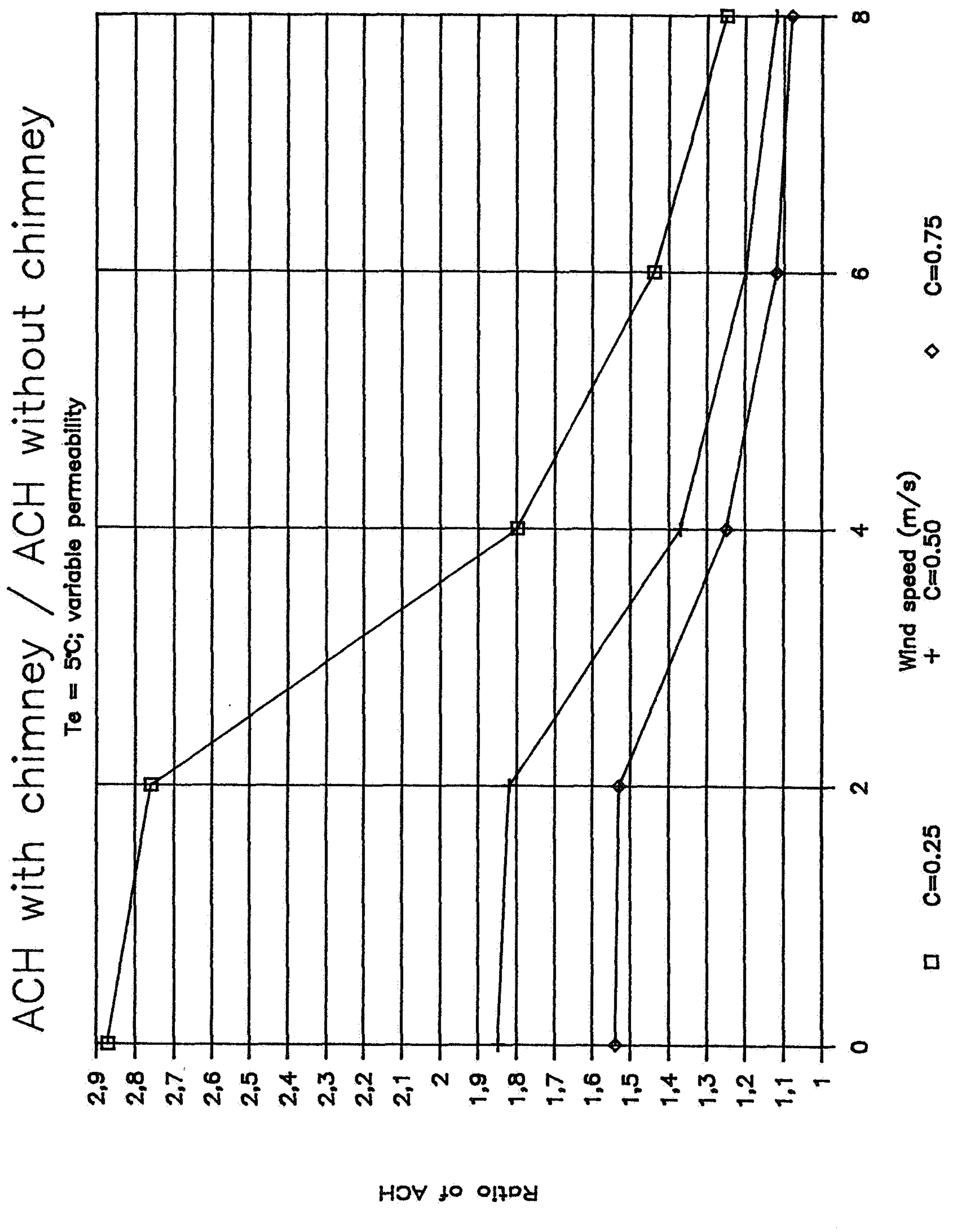

Fig. 3 - Ratio of airchanges with and without as a function of v and C, for Te = 5°C.

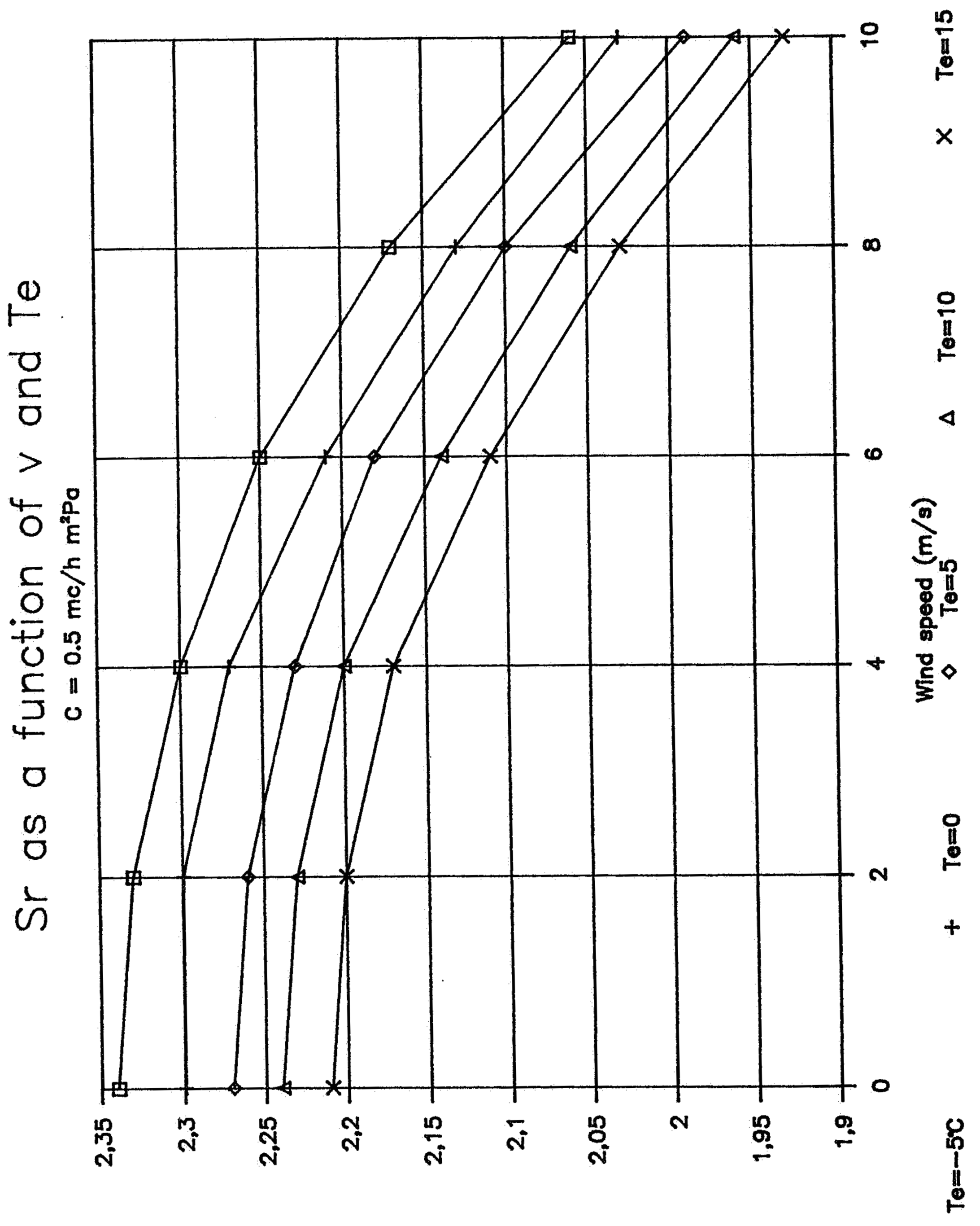

Fig. 4 - Ratio of stack mass flow to flue mass flow Sr, as a function of v and Te, C = 0.5 mc/h·m²·Pa^n.

Discussion

Paper 15

O. Nielsen (Ministry of Housing and Building, Denmark) (a) Have any Italian workers investigated the indoor climate problems associated with combustion gases back-flowing through the draft diverter? (b) I presume draft diverters are only used on boilers with atmospheric burners.

M. Masoero (Politecnico di Torino, Italy) (a) The problem has been investigated only recently. To solve it, Italgas (the largest gas distribution company in Italy) is developing a device which interrupts gas flow to the burner under the dictates of a temperature sensor at the diverter. (b) Draft diverters are compulsory on individual gas boilers with atmospheric burners, but are also used on forced air burners with the fan downstream of the draft diverter.

W. De Gids (TNO Division of Technology for Society, Holland) A problem associated with flow diverters is that immediately after the burner ignites there is an emission of NOx into the space.

R. Walker (Building Research Station, Garston, UK) (a) Could you tell me what expression you used to relate indoor-outdoor pressure differences to air leakage? (b) You may find it useful to scale data by 1/(DT)1/2 in order to remove the dependence on DT.

M. Masoero (Politecnico di Torino, Italy) (a) The usual expression:$Q = C A |Dp|n$ was used (see equations (6') and (6") in the paper).

D. Harrje (Princeton University, USA) Besides the air infiltration implications of your work it is also important to consider the soil gas and radon which may be drawn from the basement crawlspace due to the negative pressure (set up by boiler operation). If a warm air system is used there are further considerations with regard to supply and exhaust balance, which would also affect the basement area pressure.