VENTILATION SYSTEM PERFORMANCE

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Paper 15

INTERACTION BETWEEN AIR INFILTRATION AND COMBUSTION APPLIANCES - VALIDATION OF A NUMERICAL MODEL

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SYNOPSIS

This paper presents some of the early theoretical work conducted within the framework of a research program aimed at analysing the interaction between gas-fired domestic appliances and the indoor environment in terms of energy consumption, indoor air quality and operational safety.

A simplified multizone mathematical model has been developed, which is capable of analysing the thermo-fluid dynamics behaviour of the building + appliance + chimney system. A parametric study has been completed which points out the influence of factors such as outdoor temperature, wind speed, spatial distribution of building envelope permeability on the overall system performance.

LIST OF SYMBOLS

C = permeability coefficient of envelope element ($m^3/s\ Pa^n$)
C_d = flow coefficient
ΔP_{loss} = pressure losses in the heat exchanger (Pa)
ΔP_r = reference pressure difference (Pa)
K = proportionality constant $(m/kg)^2$
L = equivalent air leakage area $(m)^2$
LF = load factor of boiler
M = gas mass flow rate (kg/s)
M_{off} = gas flow in the stack in the OFF phase (kg/s)
M_{on} = gas flow in the stack in the ON phase (kg/s)
M_s = average gas flow in the stack (kg/s)
OS = boiler oversizing factor
ρ = air density (kg/m^3)
S_r = ratio of stack flow and boiler flow
T_i = indoor temperature (°C)
T_o = outdoor temperature (°C)
T_{od} = outdoor design temperature (°C)
τ_{off} = boiler OFF-time in a typical operation cycle (s)
τ_{on} = boiler ON-time in a typical operation cycle (s)

1. INTRODUCTION

Individual heating with gas-fired boilers has grown to become the most popular heating system in residential buildings in Italy. New installations are usually designed in such a way that risks of accidents due to defective exhaust of combustion products (CO poisoning) are minimised; this is normally accomplished by installing the boiler outside the living space (e.g. in a small outdoor ventilated cabinet), or adopting balanced-draft units.

Nevertheless, a significant number of existing installations, as well as new installations in refurbished dwellings where outdoor installation is not feasible, are characterised by the presence of the boiler within the living space. Fairly detailed regulations exist in Italy, which specify how a safe system should be installed. However, due to a lack of technical culture among many building contractors and insufficient information of the occupants, and because of the objective difficulty in controlling such an enormous number of existing installations, lethal accidents during the heating season are unfortunately not unusual.

The concern for safety issues, and more generally for indoor air quality problems which may arise from combustion systems, has suggested the Politecnico di Torino and the national gas utility Italgas to promote a joint research effort on these subjects. The research program, which has started in the Spring 1990, will consist both of thoretical/numerical and of experimental work. To this aim, Italgas has constructed in the vicinity of Torino two identical single-family houses, which are fully instrumented for experimental analyses concerning the performance of combustion units for space heating and cooling, the thermal behaviour of the building, the quality of indoor air, etc.

This paper presents some of the early theoretical work produced by the research program. A mathematical model has been developed and tested, which is capable of analysing the thermo-fluid dynamics interaction between a building and the boiler + chimney installed within the building itself, taking into account the geometric and air permeability properties of the building envelope, the climatic conditions at the building site, and the characteristics of the heating system. A number of analyses were conducted with the model and the most significant results are presented in the paper.

2. FEATURES OF THE MATHEMATICAL MODEL

The numerical model which is the object of this paper is an enhancement of the model developed by Fracastoro and Masoero, described in a previous AIVC conference paper /1/. Improvements with respect to the original model only are described herein; reference can be made to the previous paper for background information on the assumptions and algorithms adopted by the model.

The model can be defined as an enhanced single-zone model, since it permits a simplified multizone representation. In practice, it is possible to describe the building as constituted by vertically stacked individual zones, each corresponding to one storey; the resistance to air flow between stories is taken into account in the calculation, and ambient temperatures at various storeys can be assumed different. Furthermore, the influence of combustion appliances located within the building on airchanges can be evaluated through the analysis of the behaviour of the gas exhaust system (or "chimney"), including the flue, the draft diverter, and the stack.

2.1 Air flow through the envelope

The permeability function which characterises each element of the external envelope is determined using the equivalent air leakage area concept; the latter values are determined as a function of type, number, and extension of the openings located in the element, based on literature values of air leakage area at 4 Pa, assuming a unitary airflow coefficient /2,3,4,5/. For each envelope element, the permeability equation is determined assuming the flow exponent value and calculating the permeability coefficient with the following equation:

$$C = L\,C_d\,(2/\rho)^{1/2}(\Delta P_r)^{1/2-n} \qquad (1)$$

where:

L = equivalent air leakage area
C_d = flow coefficient
ΔP_r = reference pressure difference
ρ = air density

Assuming $\Delta P_r = 4$ Pa, $\rho = 1.29$ kg/m^3, $C_d = 1$, $n = 0.65$, eqn. 1 yields:

$$C = 1.0114\,L$$

Wind pressure is calculated using the equations for wind speed and pressure coefficients given in the AIVC Calculation Guide /3/. It is also possible to consider zero wind speed on any of the building sides.

2.2 Boiler and gas exhaust analysis

The model is capable of analysing the part-load behaviour of the boiler. Assumption is made that the boiler operates at full load when outdoor temperature reaches the winter design temperature. At partial loads, the boiler operates according to ON-OFF regulation. In order to analyse the system behaviour in the OFF phase, it is essential to calculate the load factor LF, which is defined as:

$$LF = \frac{(T_i - T_o)}{(T_i - T_{od})}(1 + OS) = \frac{\tau_{on}}{\tau_{on} + \tau_{off}} \qquad (3)$$

where:

T_i = indoor temperature
T_o = outdoor temperature
T_{od} = outdoor design temperature
OS = boiler oversizing factor
τ_{on} = boiler ON-time in a typical operation cycle
τ_{off} = boiler OFF-time in a typical operation cycle

It is assumed that flue gas temperature downstream the heat exchanger in the OFF phase is $T_{off} = 90°C$. Such assumption can be justified as follows: in small size boilers, which are typically considered in our analyses, the temperature of the metal walls delimiting the combustion chamber is virtually equal to the water temperature. Therefore, it can be assumed that, when the burner is OFF, the air temperature in the combustion chamber drops rapidly to a value which is slightly above the water temperature (typically 70 to 80°C) /6/. Pressure losses in the heat exchanger are calculated with the equation:

$$\Delta P_{loss} = K\rho M^2 \tag{4}$$

where:

K = proportionality constant
M = gas mass flow rate

under the assumption that K assumes the same value both in the ON- and OFF-phases.

The algorithm calculating the global mass balance of the system (building + boiler + gas exhaust) is basically the same in the ON and OFF phase, the major difference being that in the ON phase the gas flow through the boiler is given and constant (being a function of the constant power delivered by the boiler), while in the OFF phase the gas flow is no longer known "a priori", but must be calculated within the overall iterative procedure. Indicating with M_{on} and M_{off} the gas flow in the stack in the ON and OFF phase respectively, the average stack flow can be estimated as:

$$M_s = M_{on}\,LF + M_{off}\,(1 - LF) \tag{5}$$

This approach permits to take into account the influence on gas flow of the time variations of gas temperature due to intermittent operation. Obviously, in real operation the gas temperature varies continuously rather than assuming two distinct values, as assumed above; however, the inaccuracies introduced by such approximation are negligible and no significant improvements would be obtained by assuming a continuous temperature trend.

2.3 Limits of the model

Compared to a standard single-zone model, this model permits to analyse multi-storey buildings, albeit in a simplified manner. Strictly speaking, each zone (viz. storey) should include a single dwelling with rooms connected by large openings, so that no significant flow resistance exists between rooms; nevertheless, useful results can be obtained even with relatively complex buildings, particularly if the main goal of the analysis is to evaluate the interaction between envelope permeability and boiler operation.

A noteworthy limitation concerns the assumptions for wind pressure calculation: such assumptions only apply if the building height does not exceed about 10 to 12 m.

3. RESULTS OF THE MODEL

The results presented in Table 1 and in Figures 1 through 4 are based on the following assumptions:

- the floor plan of the building is square, 15 x 15 m;
- the building consists of three storeys, respectively 2.5 m, 3.0 m and 3.0 m high;
- the temperature of the lower storey (unheated) is 5°C, while for the two upper storeys (heated) is 20°C;
- there are no obstructions around the building;
- each size of the building has the same permeability, the average value being $0.63 \text{ m}^3/\text{h m}^2 \text{ Pa}^n$;
- each of the two upper storeys is heated by an individual boiler;
- wind speed is 2 m/s;
- outdoor temperature is -5°C;
- internal air flow resistance between storeys is 0.5.
- in the graphs showing temperature differences, 1 indicates the upwind wall (orthogonal to wind direction), 2 the leeward wall, and 3 and 4 the two walls parallel to wind direction.

The model was been employed to investigate parametrically the interaction between the building structure and the boiler plus chimney system. In particular the following aspects were analysed: i) the influence of the presence of one or more boilers on the overall value of natural airchanges; and ii) the influence of envelope permeability on boiler operation under various meteorological conditions, aiming at identifying the potentially dangerous situations when gas exhaust becomes critical.

The type of building considered in the parametric analysis is the same as in the above example; four different cases for the distribution of envelope permeability were considered:

1 - high-leakage building with equal permeability of all sides ($0.63 \text{ m}^3/\text{h m}^2\text{Pa}^n$ - ASHRAE class G);
2 - low-leakage building with equal permeability of all sides ($0.20 \text{ m}^3/\text{h m}^2\text{Pa}^n$ - ASHRAE class D);
3 - perfectly airtight (ASHRAE class F) upwind side, the other three sides as in case 1);
4 - perfectly airtight (ASHRAE class F) leeward side, the other three sides as in case 1).

As a result of the parametric analysis, the following quantities were calculated:

- overall buiding airchanges;
- total gas flow through the stacks;
- ratio of stack flow and boiler flow (the difference between the two being the flow through the flow diverter), indicated in the following as S_r.

The variable parameters in the analysis were:

- wind speed;
- outdoor temperature;
- useful height of the stack;
- boiler operation (ON-OFF vs. steady-state).

In the previously presented paper /1/, it was shown that the gas flow through the stack decreases as both wind speed and outdoor temperature increase. Figures 5 and 6 give the gas flow values in the case of ON-OFF and steady-state operation. The graphs indicate that the gas flow decreases as outdoor temperature increases more markedly in the case of intermittent operation than in steady-state. This result can be explained by the fact that in ON-OFF operation both the boiler load and the stack draft are reduced.

The graphs of Figures 7 and 8 allows the comparison of overall airchanges in the cases of intermittent (50% load factor) and steady-state boiler operation. The ACH variation shown in Fig. 7 between operations is minimal, and can be detected only for very low wind speeds and high internal flow resistance. The variation of gas flow through the stack, given in Fig. 8, is on the order of 10% and is only marginally influenced by wind speed and internal flow resistance.

It has been observed that the reduction of natural airchange due to the increase of outdoor temperature may be offset, in some cases, by the reduction of the overpressure created by the stack at the boiler level: in such case, the gas flow through the stack turns out to be virtually constant with varying outdoor temperatures. This situation may occur when the boiler is located well below the neutral plane of the building, in the case that a single boiler is installed for heating the two upper storeys.

Figures 9 and 10 permit to evaluate the influence of envelope permeability on the airchanges and boiler operation. The graph of Fig. 9 shows how the variations in envelope permeability affect the building overall airchanges with respect to the reference high leakage envelope (building 1). As expected, a reduction of permeability greatly reduces the building airchanges: with wind speed equal zero, the airchanges with a low permeability envelope (building 2) are about a half the airchanges of building 1. If wind speed equals zero, the presence of a perfectly airtight wall determines a reduction of overall airchanges on the order of 20% (buildings 3 and 4). For high wind speed (e.g. 4 m/s), the position of the airtight wall becomes important: in the upwind case (building 3), the reduction of airchanges is significant (about 50%), while in the leeward case (building 4), only a 10% reduction is found with respect to building 1. The graph of Fig. 10 shows the effect of envelope permeability on the stack flow ratio S_r (stack flow / boiler flow). From this graph it can be noticed that the variation in stack flow due to wind effect is negligible in all cases, except if the upwind wall is perfectly airtight and the wind speed is high (building 3). A reduction of gas flow in the stack is a symptom that critical conditions may be reached with respect to combustion products exhaust: in the limit case, gases may be discharged indoors through the flow diverter.

In Figures 11, 12 and 13 the ratio S_r is given as a function of stack height and wind speed. The results were calculated assuming that the overall length of the gas exhaust system is constant and equal to 3 m, for varying stack height. A potentially dangerous situation is encountered when the ratio S_r decreases and approaches the unit value: in such case, the pressure difference across the flow diverter becomes zero and flow reversal can therefore occurr. The stack height value for which S_r reaches one may therefore be defined as the "critical height" of the stack. The graphs show that the critical height increases as the envelope permeability decreases, when the wind speed is zero. For intermediate wind speeds, the critical height is the same for the permeability cases 2) and 3), even if in case 3) the average permeability is much higher; this is due to the fact that in case 3) the presence of an airtight upwind wall induces a significant reduction of indoor pressure. Finally, for very high wind speeds, the critical height is first reached in the case of upwind airtight wall.

4. CONCLUSIONS

The results presented in this paper indicate that mathematical modeling of the interaction between building structure, boiler and chimney may provide useful guidelines concerning the proper installation of combustion equipment within inhabited spaces. The overall behaviour of the system was analysed under varying conditions with respect to climate, envelope construction and boiler operation. It is particularly interesting to notice that, with respect to safety, it is not only important to provide an adequate envelope leakage, but also to properly locate the ventilation openings with respect to dominant wind directions.

REFERENCES

/1/ Fracastoro G.V., Masoero M. "*Air infiltration induced by heating appliances*" Proc. 9th AIVC Conference, Gent, 1988.

/2/ ASHRAE Handbook of Fundamentals, Ch. 23 "*Infiltration and Ventilation*", 1989.

/3/ Liddament M.W. *Air infiltration calculation techniques - An application guide*, AIVC, 1986.

/4/ Baker P.H., Sharples S., Ward I.C. "*Air flow through cracks*" Building and Environment, Vol. 22, No. 4, 1987.

/5/ ASHRAE Standard 119 - *Air leakage performance for detached single family residential buildings*, 1989.

/6/ Anglesio P. et al. "*Prestazioni termofluidodinamiche dei camini*" (Thermal and fluid dynamics performance of chimneys - in Italian), Politecnico di Torino, Research Report CNR 85.00898.59, 1987 (unpublished).

Table 1 - Sample of model output

Normalised equivalent leakage area = ...0.6249
Airtighteness class (according to ASHRAE Standard) = ...G
Internal flow resistance coefficient = ...0.50
Outdoor temperature = ...-5°C
Local wind speed at 10 m height = ...2.01 m/s
Overall building airchange = ...0.156 ach
Air flow out through building envelope = ...182.9 m^3/h

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BOILER # 1
Stack cross section = ...0.0079 m^2
Useful stack height = ...3.0 m
Boiler output = ...23.6 kW
Boiler load factor = ...89.3 %
Flow through draft diverter, ON phase = ...15.0 m^3/h
Flow through boiler, ON phase = ...36.5 m^3/h
Flow through draft diverter, OFF phase = ...1.4 m^3/h
Flow through boiler, OFF phase = ...4.1 m^3/h
Stack/Boiler flow ratio, ON phase Sr = ...1.41
Stack/Boiler flow ratio, OFF phase Sr = ...1.25
Gas temperature at boiler exit, ON phase = ...271.1°C
Gas temperature in the stack, ON phase = ...198.7°C
Gas temperature at boiler exit, OFF phase = ...90.0°C
Gas temperature in the stack, OFF phase = ...77.2°C
Gas speed at boiler exit, ON phase = ...2.69 m/s
Gas speed in the stack, ON phase = ...3.29 m/s
Gas speed at boiler exit, OFF phase = ...1.66 m/s
Gas speed in the stack, OFF phase = ...2.01 m/s

BOILER # 2
Stack cross section = ...0.0079 m^2
Useful stack height = ...3.0 m
Boiler output = ...23.6 kW
Boiler load factor = ...89.3 %
Flow through draft diverter, ON phase = ...17.6 m^3/h
Flow through boiler, ON phase = ...36.5 m^3/h
Flow through draft diverter, OFF phase = ...1.7 m^3/h
Flow through boiler, OFF phase = ...4.3 m^3/h
Stack/Boiler flow ratio, ON phase Sr = ...1.48
Stack/Boiler flow ratio, OFF phase Sr = ...1.30
Gas temperature at boiler exit, ON phase = ...272.1°C
Gas temperature in the stack, ON phase = ...190.2°C
Gas temperature at boiler exit, OFF phase = ...90.0°C
Gas temperature in the stack, OFF phase = ...75.6°C
Gas speed at boiler exit, ON phase = ...2.69 m/s
Gas speed in the stack, ON phase = ...3.39 m/s
Gas speed at boiler exit, OFF phase = ...1.76 m/s
Gas speed in the stack, OFF phase = ...2.19 m/s

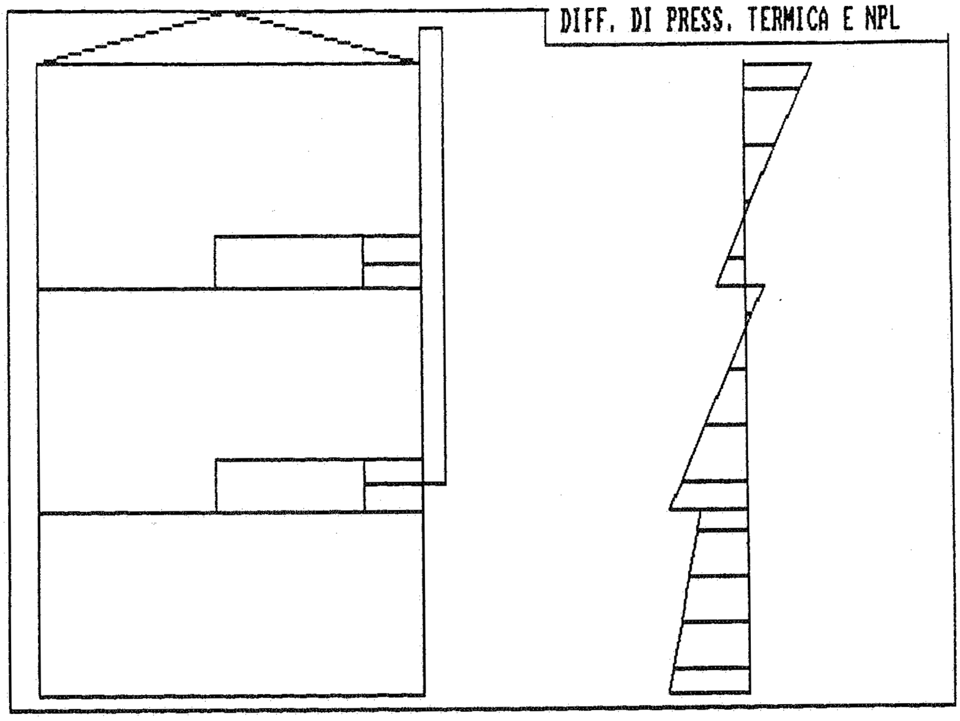


Fig.1 - Total pressure difference and neutral plane level

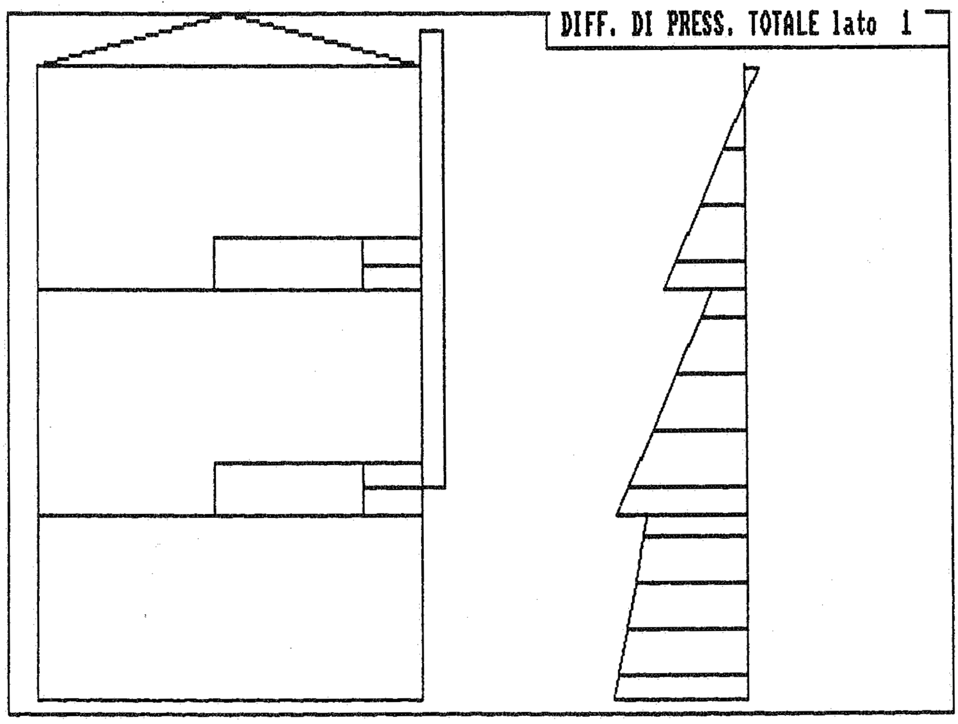


Fig.2 - Total pressure difference, wall 1 (upwind)

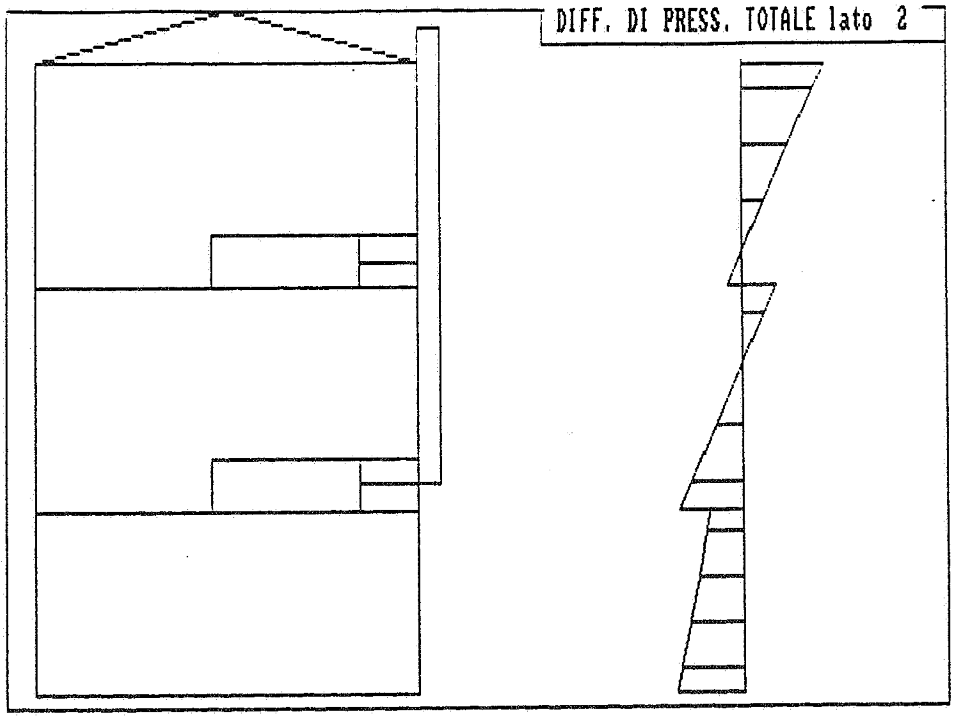


Fig.3 - **Total pressure difference, wall 2 (downwind)**

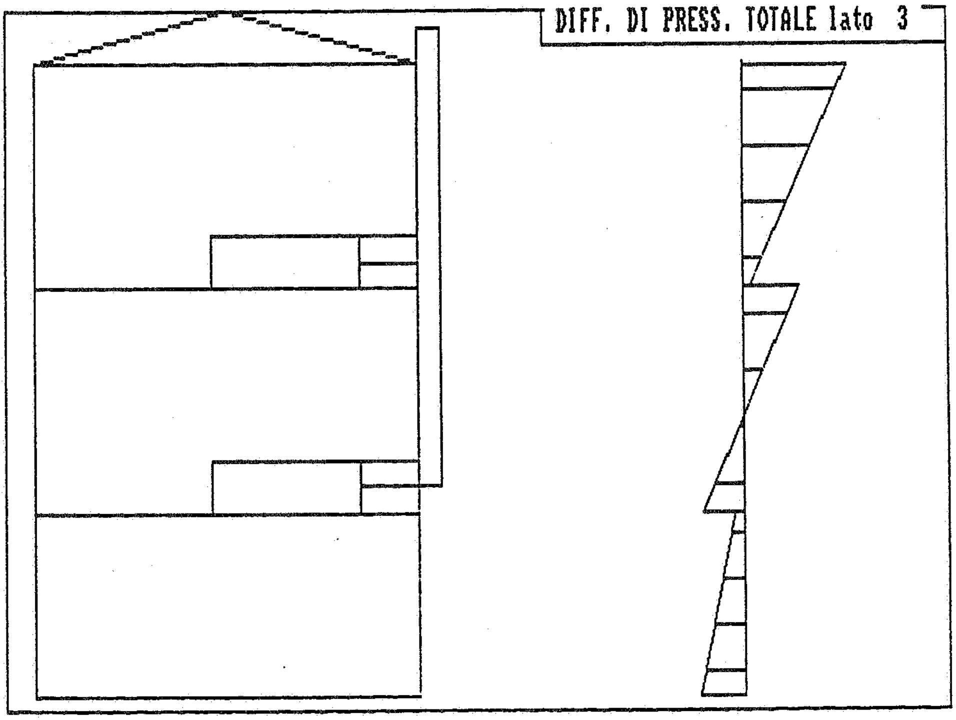


Fig.4 - **Total pressure difference, wall 3 (lateral)**

Fig. 5 — Flow rate through stack

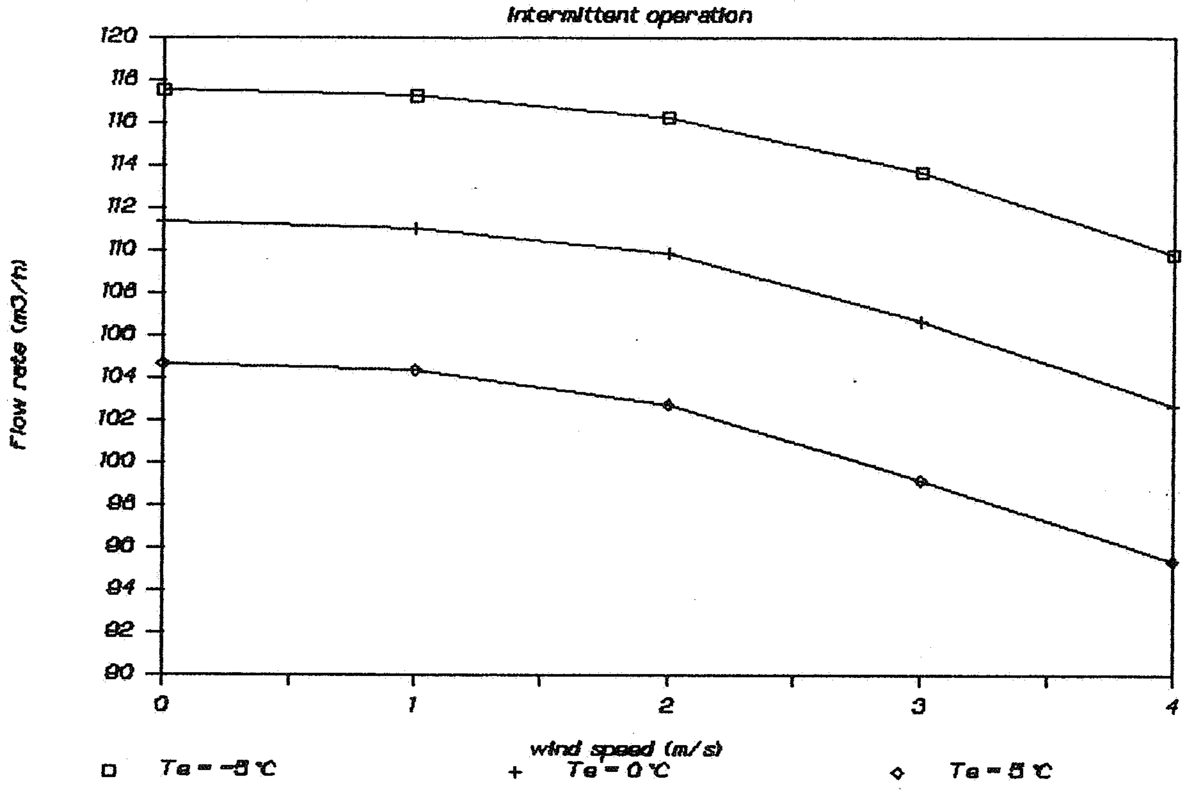


Fig. 6 — Flow rate through stack

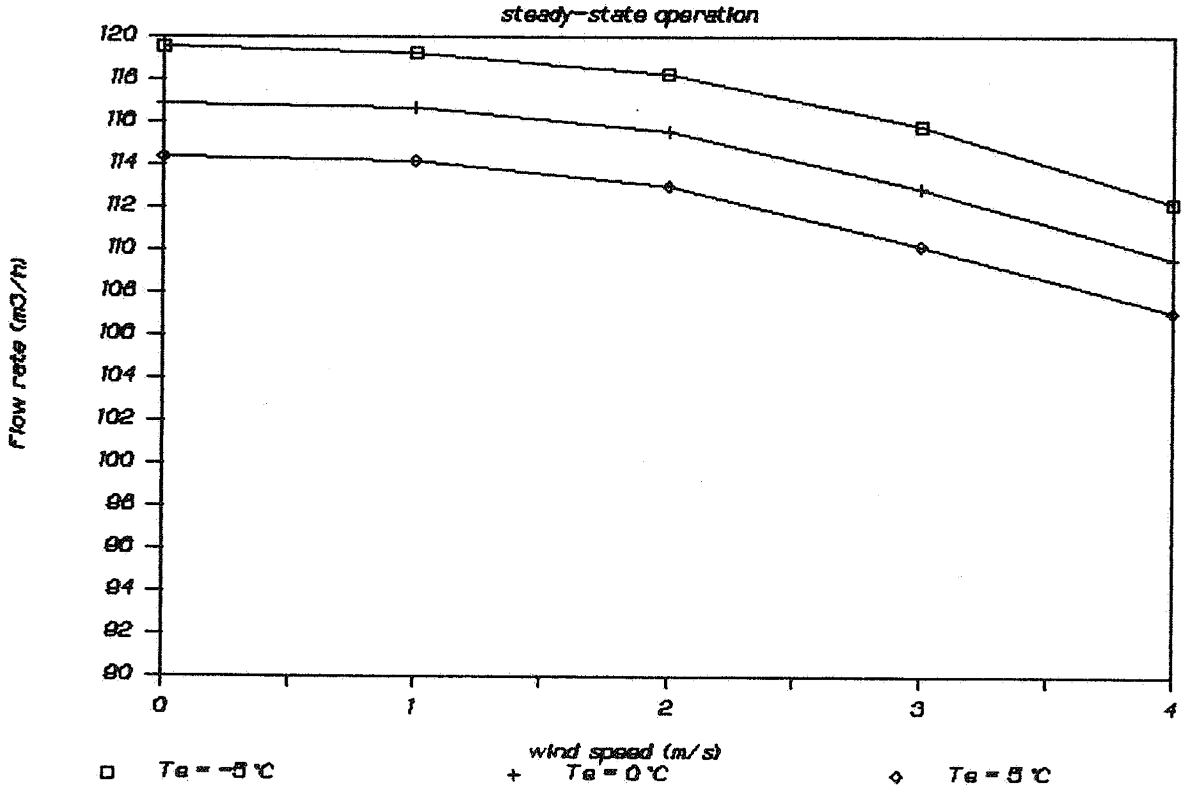


Fig.7 – ACH Ratio on-off/steady-state

Te = 5 °C

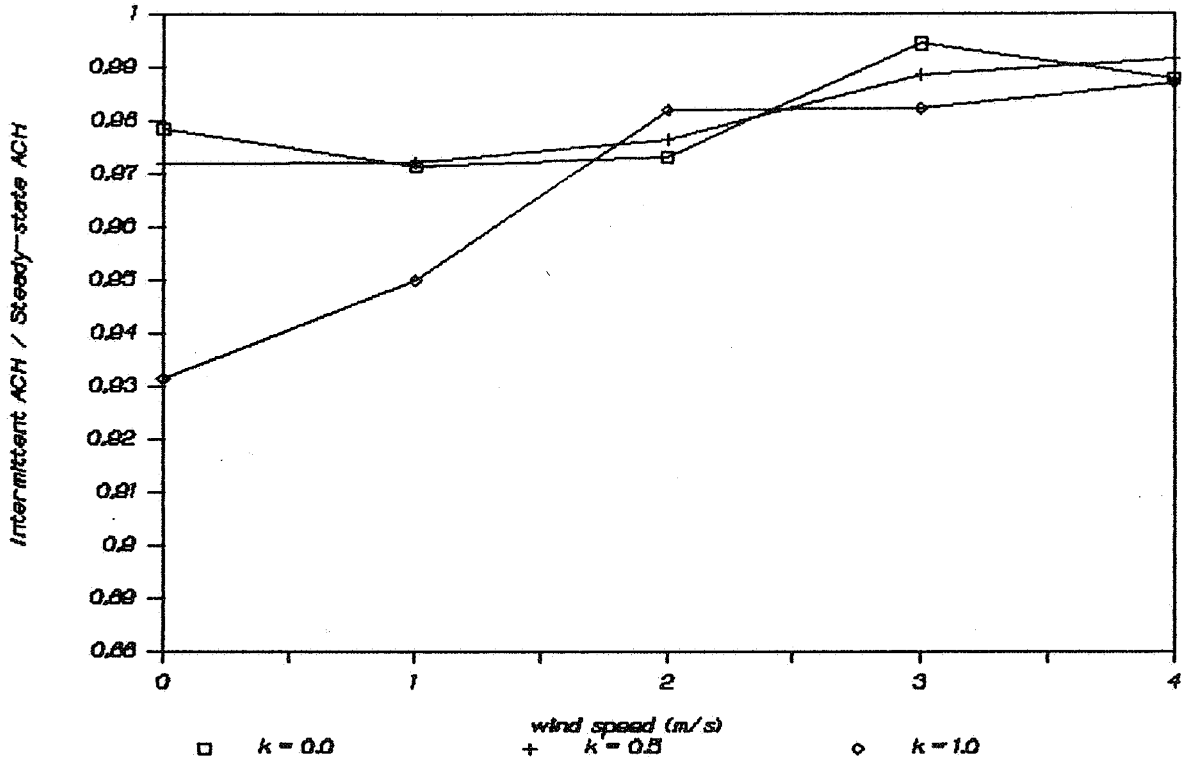


Fig. 8 – Stack flow ratio

on-off/steady-state, Te = 5 °C

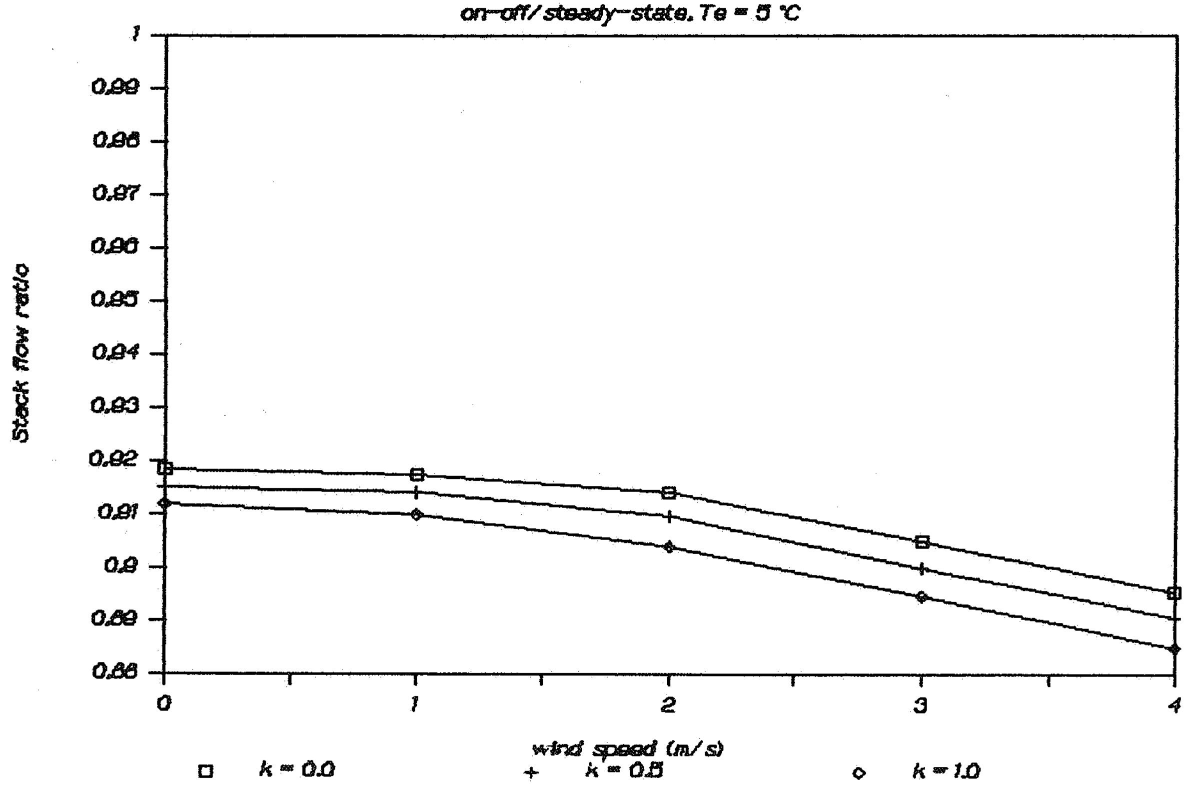


Fig. 9 – ACH ratio to building #1

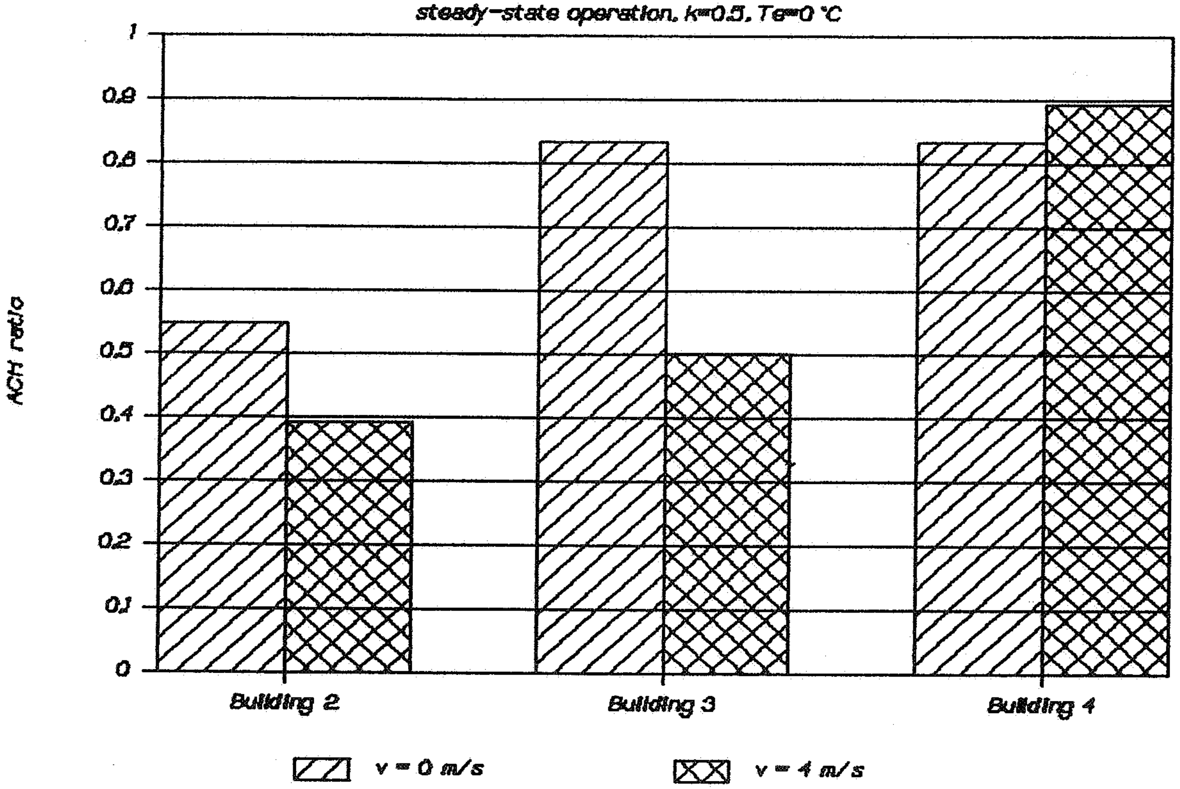


Fig. 10 – Stack flow ratio to bldng. #1

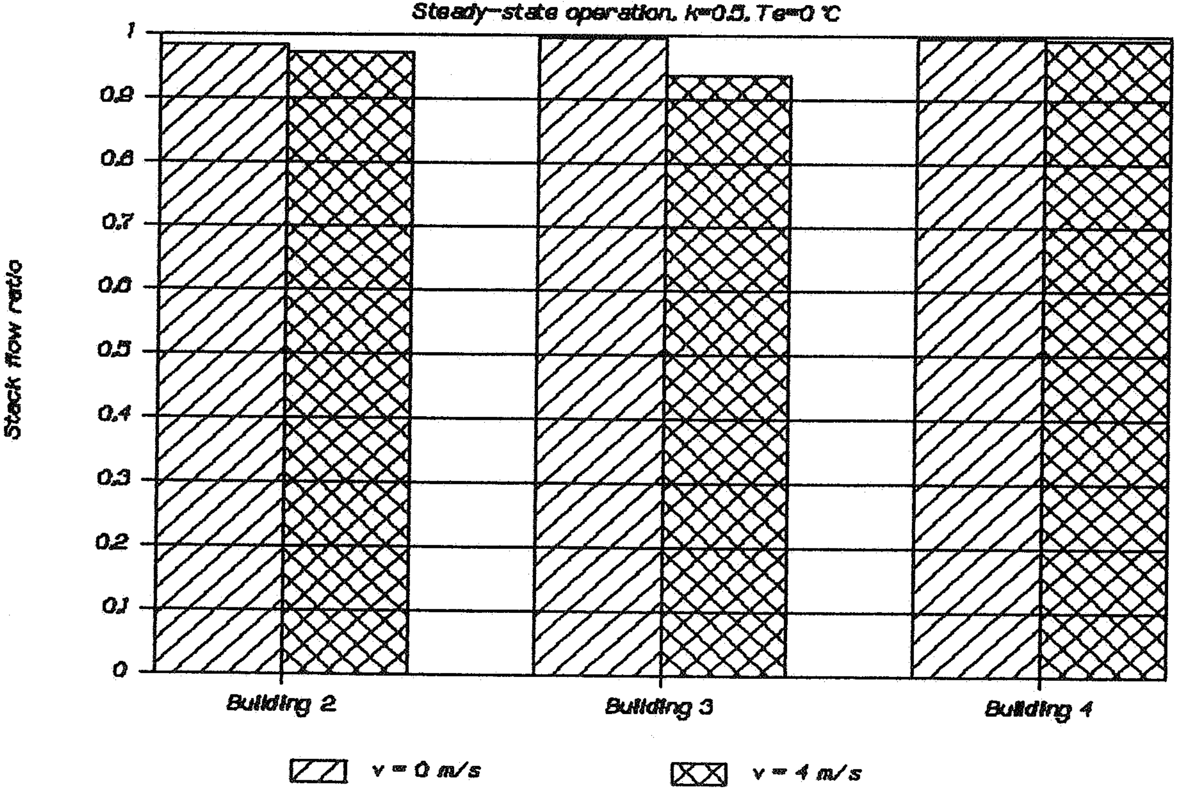


Fig. 11 – Sr vs. useful stack height

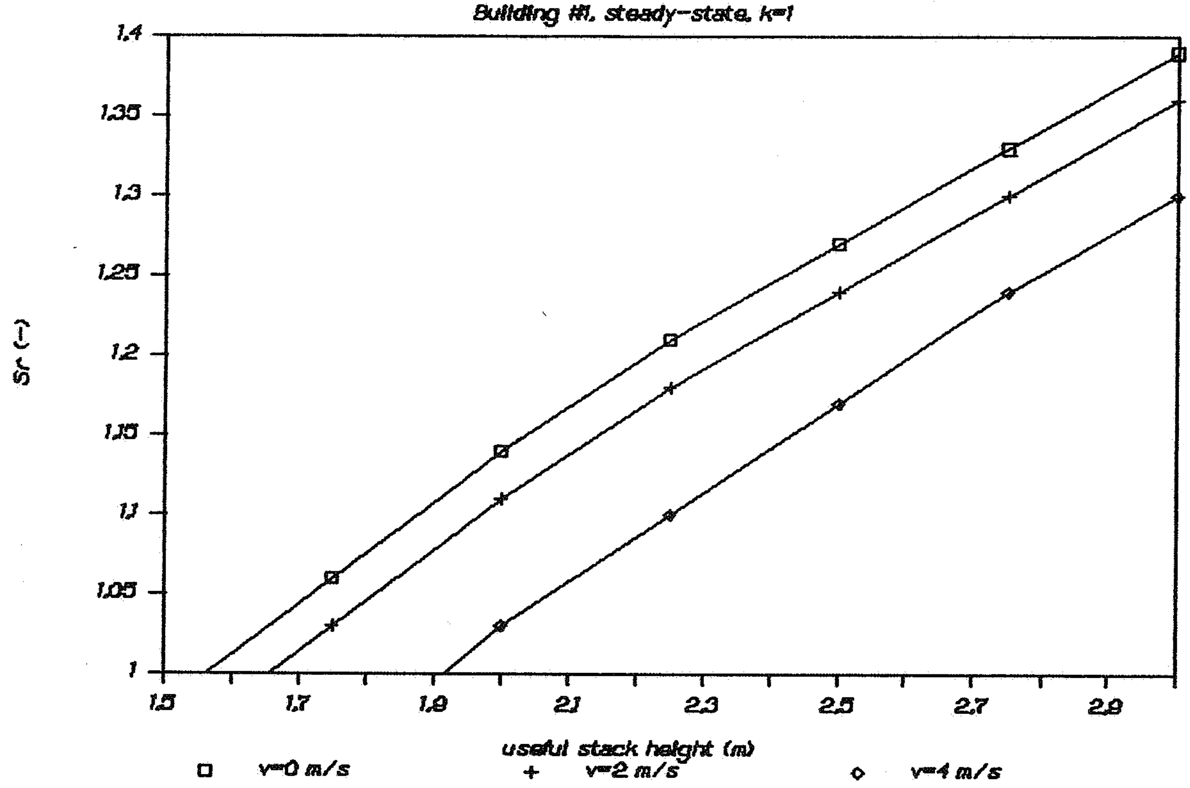


Fig. 12 – Sr vs. useful stack height

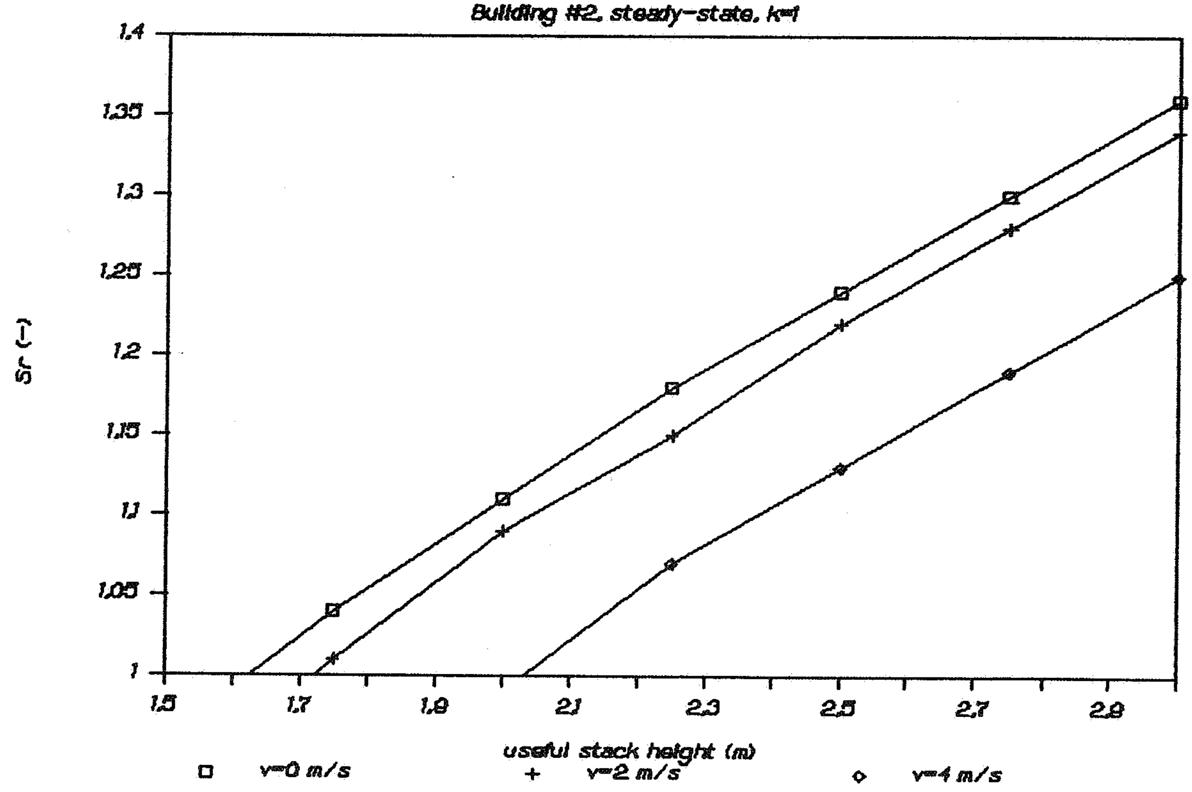
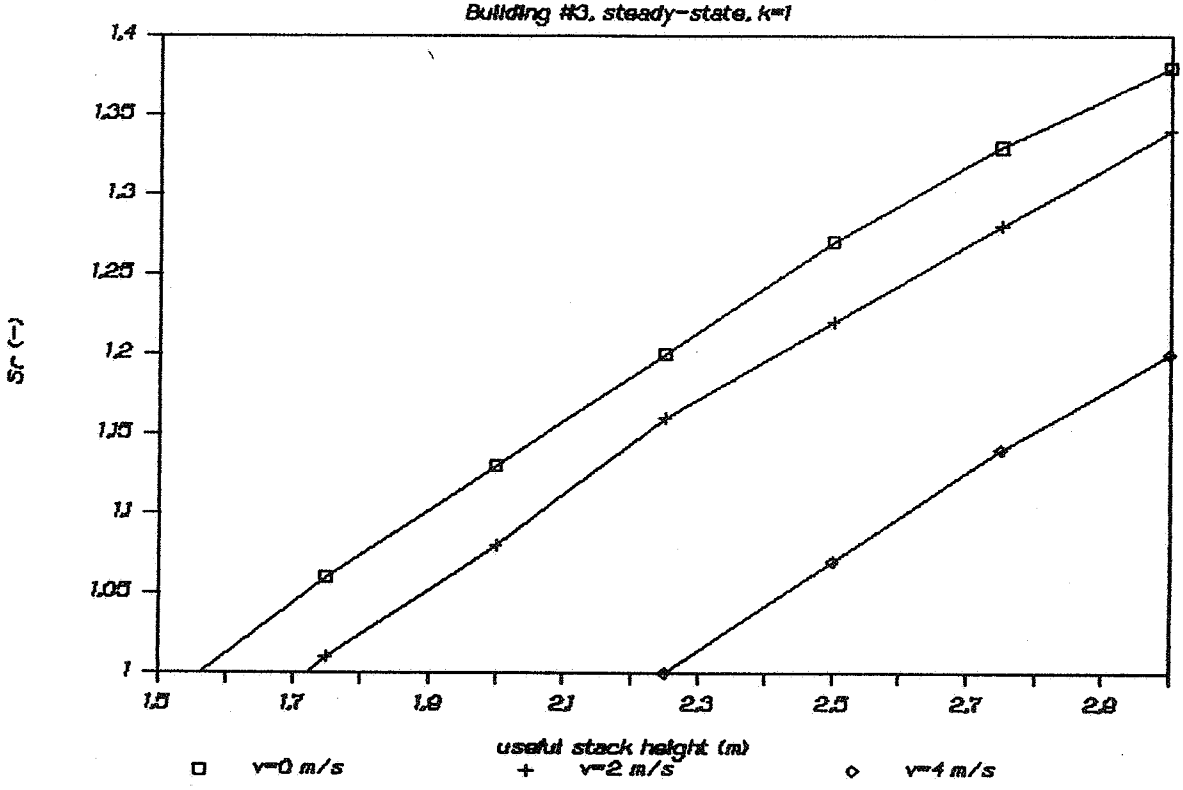


Fig. 13 – Sr vs. useful stack height

Building #3, steady-state, k=1



Discussion
Paper 15

D. Bienfait (CSTB, France)

We found that air flow in the stack increases with increasing wind speed due to the negative Dp induced by the wind on the top of the stack. Your results show an opposite trend. Why?

G Fracastoro & M Masoero (Politecnico Torino, Italy)

Because we adopted, as a conservative assumption, Dp = 0, due to the absence of reliable experimental data on the pressure coefficient at the top of the chimney, which can vary from 0 to 0.7.

J Van Der Maas (LESO, Switzerland)

Comment: The effect of turbulence on ventilation should be studied in the presence of temperature differences, because else there is a tendency of no-mixing (the incoming air goes immediately out).