CALCULATION METHOD FOR THE NATURAL VENTILATION OF BUILDINGS.

W.F. de Gids

S U M M A R Y

After a short review of the mechanism of natural ventilation, a prediction method for the calculation of the air flow rate through buildings is described.
Comparison with measurements shows rather good agreement.

P n by

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CALCULATION METHOD FOR THE NATURAL VENTILATION OF BUILDINGS. *)

By W.F. de Gids

1. Introduction

Even now, most buildings are still naturally ventilated. So natural ventilation is an important factor. Nevertheless quantitative values for natural ventilation are unknown in most cases. Sometimes it is necessary to know this ventilation rate with regard to an indoor environment. On the other hand, ventilation is a source of heat loss. To make a good energy balance it is desirable to be able to predict the air flow rate through a building due to natural ventilation. As natural ventilation depends on so many variables it is unfeasible to develop a prediction method based on pure physical phenomena.
The calculation method described can be seen as a reasonably accurate approach. The method can be used only if the pressure distribution on the outside of the building is known, or can be estimated from figures in literature.
In this paper the calculation method developed is compared with the results of measurements in a large factory hall.

2. Natural ventilation

The natural ventilation of buildings depends on wind velocity, wind direction, temperature differences between inside and outside, the form of the building and its situation, the openings in the building and last but not least the occupants' behaviour.
The relationship between the above mentioned variables and the natural ventilation is schematically represented in figure 1.

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2.1 Pressure differences due to wind

If there is a building in a particular situation, the wind causes pressure differences. This wind pressure distribution will depend on the interrelation between the wind velocity, wind direction and the exposure, and the form and situation of the building.
It can be expressed as:

$$\Delta p_i = k_i \cdot \tfrac{1}{2} \rho v^2 \quad \text{where} \qquad (1)$$

Δp_i = pressure difference across an external wall or across a ventilation duct [Pa]

k_i = dimensionless pressure coefficient depending on the form of the building and the exposure [-]

ρ = air density [kg/m^3]

v = wind velocity [m/s]

For each wind direction there are different pressure differences across the different walls (i), which we call the pressure distribution.

2.2 Stack effect

Temperature differences between inside and outside cause differences in air density and result in pressure differences. This can be expressed as:

$$\Delta p = (\rho_c - \rho_w) \cdot g \cdot h \quad \text{where} \qquad (2)$$

Δp = pressure difference (stack effect) [Pa]

ρ = air density [kg/m^3]
c = cold air
w = warm air

g = gravitational force [N/kg]

h = height between inlet and outlet openings [m]

2.3 Air flow through openings

Inevitable joints, cracks and gaps, but also special ventilation provisions such as ventilation windows, grilles or ducts are the cause of an air flow through the building.
The relation between the individual air flow through any opening and the pressure difference across the latter can be expressed as:

$$\Phi_j = C_j \, (\Delta p_j)^{1/nj} \qquad \text{where} \qquad (3)$$

Φ_j = volume flow rate of air [m^3/s]

C_j = air flow coefficient, defined as the volume flow rate of air at a pressure difference of 1 Pa [m^3/s at 1 Pa

Δp_j = pressure difference across the opening [Pa]

n = an exponent, between 1 and 2, depending on the character of the flow. [-]

n= 1 for pure laminar flow

n= 2 for pure turbulent flow

See figure 2

Measurements on windows in existing dwellings and at the laboratory indicate that for most window cracks the value of n varies between 1,4 and 1,7.
The equation (3) is based on experimental data. The Reynolds number will influence the values of both C and n.
In case of natural ventilation we are dealing with flows due to pressure differences between about 1 to 100 Pa.
Taking this into consideration, together with the experimental data, the empirical equation (3) is acceptable for flow through openings.
For calculation of C values see appendix 2.

2.4 Occupants' Behaviour

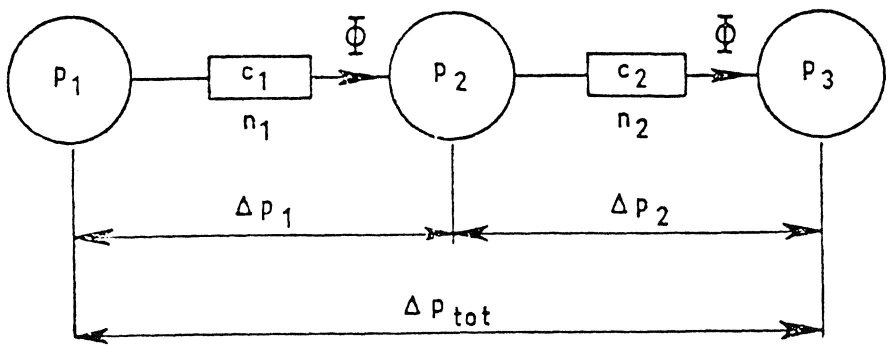
An important factor for the natural ventilation is the use made of the ventilation provisions by the occupants of the building.
The occupants' control or influence on the actual ventilation rate by opening or closing windows doors ventilationgrilles etc.
About this occupants' behaviour very few studies are known.
More studies in this field must be carried out to give usable figures to predict the natural ventilation.

3. The model of the ventilation through a building

A building usually consists of external and internal walls and a roof. These parts of the building very often have ventilation openings. Through these openings the air passes in and out of the building. See figure 3.
Figure 4 shows a ventilation model of a building. At any place in the plan of the building where air flows through openings an air leakage component with the sign[-□-] is placed in figure 4. For each component equation (3) can be applied.
It is interesting to investigate how such models can be simplified.
If this is generally possible, we would be able to derive some figures which can be used in many cases.
Figure 4 shows parallel and series connections from inside to outside the building.

3.1 Series connections

The scheme is as follows:



The equations for series connections are:

$$\Delta Ptot = \Delta p_1 + \Delta p_2 \qquad (4)$$

$$\Phi_1 = C_1 \cdot (\Delta p_1)^{1/n_1} \qquad (5)$$

$$\Phi_2 = C_2 \cdot (\Delta p_2)^{1/n_2} \qquad (6)$$

Substituting (5) and (6) in (4):

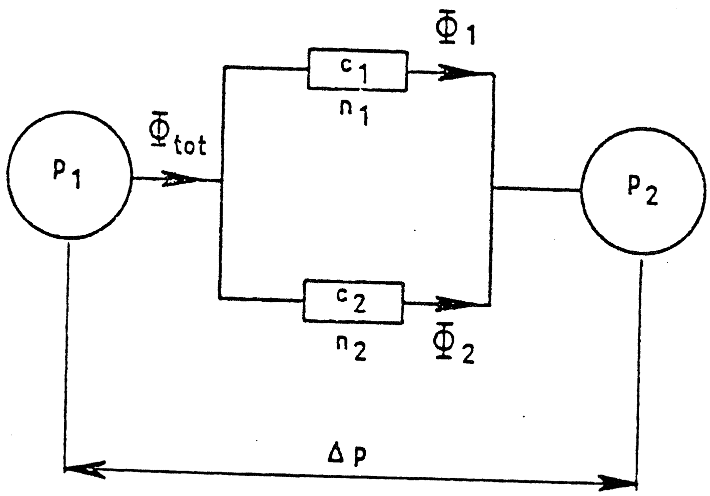
$$\Delta p_{tot} = \left(\frac{\Phi}{C_1}\right)^{n_1} + \left(\frac{\Phi}{C_2}\right)^{n_2} \qquad (7)$$

The flow (Φ), C1, n_1, C2, n2 being known, one can calculate the pressure difference.

If the pressure difference is given, the flow can be calculated by iteration only, because of the nonlinearity of equation (7).

3.2 Parallel connections

Schematically represented by:



The equations for parallel connections are:

$$\Phi tot = \Phi_1 + \Phi_2 \qquad (8)$$

$$\Phi_1 = C_1 \cdot (\Delta p)^{1/n_1} \qquad (9)$$

$$\Phi_2 = C_2 \cdot (\Delta p)^{1/n_2} \qquad (10)$$

Substituting (9) and (10) in (8):

$$\Phi_{tot} = C_1 (\Delta p)^{1/n_1} + C_2 (\Delta p)^{1/n_2} \qquad (11)$$

The pressure difference (Δp), C_1, C_2, n_1 and n_2 being known, it is possible to calculate the flows.

Graphically this can be seen from figure 5.
The question arises, is it possible to replace series and parallel connections by one single air leakage component of the form:

$$\phi = C_r(\Delta p)^{1/n_r} \quad \text{where} \qquad (12)$$

r = replaced component

From figure 5 and the equations (7) and (11) it can be seen that, mathematically, this is impossible.
Taking into consideration the pressure difference range from about 1 to 100 Pa and real n values of 1,4 to 2, figure 6 shows that the approximate equation (12) can be used.
In this pressure difference range the inaccuracy of this approximation is up to about 4%. In most cases, however, it is less than 2%.
Equations can be given to calculate the C and n values for the approximate equation.
They are beyond the scope of this paper.
In most cases it seems to be possible to simplify the model to two-junction models (see figure 7), in many cases even to one-junction models (see figure 8).

4. Calculations with a one-junction model

4.1 Calculation method

With a simple computer program, for 5 ratios of C-values and particular n-values, calculations have been made to solve the equation:

$$C_1 \ (\text{ABS}\ [p_4 - p_1])^{1/n_1} + C_2(\text{ABS}\ [p_4 - p_2])^{1/n2} + C_3\ (\text{ABS}\ [p_4 - p_3])^{1/n_3} = 0 \qquad (13)$$

if $p_4 - p_i < 0$ then C_i becomes $-C_i$
In this equation p4 is the only unknown variable. The solution can be found by iteration only.

4.2 Calculation results

Figure 9 shows a solution of p4, plotted against p3, with p2 as a variable. In the diagrams $p_1 = 0$. The ratio of $C_1:C_2:C_3 = 1:0,75:2$ and $n_1 = n_2 = 1,5$, $n_3 = 2$.
On the vertical axis the solution of p4 in a particular case is found. Knowing p4 it is easy to calculate the flows. The results of these calculations are plotted in figure 10. With the solution for p4 on the horizontal axis and p2, the other variable, one can find on the vertical axis $\Phi_{tot.rel.}$

$\Phi_{tot.rel.}$ = the total relative air flow rate through the model

If C_1 is not 1 but for instance X, one has to multiply $\Phi_{tot.rel.}$ by X to get the total air volume flow rate through the building.

Figures 9 and 10 can be combined (see figure 11)
In appendix 1 the results of calculations with 5 C-value ratios for $n_1 = n_2 = 1,5$ and $n_3 = 2$ are given.

The C-value ratios are:

C_1	:	C_2	:	C_3
1	:	1	:	1
1	:	1	:	2
1	:	1	:	4
1	:	0,5	:	2
1	:	0,75	:	2

4.3 Discussion and remarks on the diagrams

- The lines plotted in the diagrams of appendix 1, have different bending-points. All these points can be predicted. Any part of a line between two bending-points gives a particular flow direction in the three branches of the one-junction model. For instance if $p_3 = p_4$ then the flow in the branch of component 3 ($\Phi 3$) must be zero.

Before that point i.e. $p4 > p_3$ the direction of the flow is from inside to outside; if $p4 < p3$ then the flow direction in branch 3 is exactly the opposite.

- The chosen n-values seem to be useful for window and door cracks, with a mean value of 1.5.
  For ventilation grilles and ducts n=2 can be used.

5. Application and comparison

In a factory hall, with a capacity of about 87 000 m^3 (see figure 12) a large number of measurements has been done, to find the relation between air flow pattern, temperature distribution and spread of dust. [6]

In this factory hall the air velocity in every opening was measured during periods of about four hours. In total some hundreds of air velocities have been measured. From these velocities and the net area of the openings, the mass flow through the factory hall could be computed.
Pressure differences across the openings have been measured with the aid of five differential low pressure transducers. Also, the mass flow has been computed from these data. At least the different mass flows and the resulting air change rate with the calculation method described have been predicted.
In figure 13 the model of the factory hall and the conditions in the hall are shown. From table 1 can be seen that the measured and the calculated values agree rather well.
Table 2 shows values calculated with the method described above especially for the engineering department of the factory.
The air change rate (h^{-1}) is given as a function of:

- wind velocity
- wind direction
- position of the ventilation openings

6. Conclusions

6.1. - It seems to be possible to simplify parallel and series connections (with an inaccuracy of less than 4%) in a network of a ventilation model.

6.2. - Ventilation models of buildings can often be simplified to one-junction models.

6.3. - In that case, if the pressure distribution and the air leakage coefficients of the openings in the building are given, or can be calculated, one can predict the air flow through a building using appendix 1.

6.4. - In more complicated situations a digital computer program can predict the air flow through buildings.

6.5. - Comparison of predicted and measured values seems to show a reasonable agreement. (see also ref. [5])

7. References

[1] Shaw, W.N. Air currents and the laws of ventilation, London, Cambridge at the University Press, 1907.

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[6] Boekesteijn, P. a.o. Air movement in buildings, Delft, IG-TNO, 1977, Report no. C 384.

[7] Recknagel, H. and E. Sprenger. Taschenbuch für Heizung- und Klimatechnik, München, Oldenbourg Verlag, 1977.

8. Nomenclature

A	= Area of ventilation opening	[m^2]
C	= Air flow coefficient	[m^3/s at 1Pa]
c	= specific air flow coefficient	[m^3/s , m crack length at 1Pa]
d	= diameter	[m]
g	= gravitational force	[N/kg]
h	= height	[m]
K	= dimensionless pressure coefficient	[-]
l	= length	[m]
n	= an exponent, between 1 and 2, depending on the character of the flow	[-]
p	= pressure	[Pa]
Δp	= pressure difference	[Pa]
ΔT	= temperature difference	[K]
v	= wind velocity	[m/s]
w	= width	[m]
α	= wind direction	[°]
ζ	= velocity prssure factor	[-]
λ	= friction coefficient	[-]
μ	= constriction factor	[-]
ρ	= air density	[kg/m^3]
Φ	= flow (mass or volume)	[kg/s] [m^3/s]

Subscripts

1, 2 ... 4	identification number of a variable
i, j	unknown numbers of variables
c	cold air
w	warm air
r	replaced
tot.	total
tot. rel.	total relative

Appendix 1

Diagrams

C -value ratio

	C1	:	C2	:	C3
1.1.	1	:	1	:	1
1.2.	1	:	1	:	2
1.3.	1	:	1	:	4
1.4.	1	:	0,5	:	2
1.5.	1	:	0,75	:	1

Appendix 2

Calculation of air leakage coefficients

2.1. Open windows and doors

2.2. Ducts, grilles etc.

2.3. Cracks, gaps, joints etc.

Appendix 2

2.1. Calculation of air leakage coefficients

Open windows and doors

For the calculation of the turbulent flow through these ventilation openings the following equations can be used.

$$C = \frac{A \cdot \mu}{\sqrt{1/2\ \rho}} \qquad (14)$$

where C = air leakage coefficient [m^3/s at 1Pa]

A = area of the ventilation opening [m^2]

μ = constriction factor (0.67) [-]

ρ = air density [kg/m^3]

2.2. Ducts, grilles etc.

As the flow in practice will in most cases be turbulent the C-value can be calculated from the relation

$$C = \frac{A}{\sqrt{1/2\ \rho \cdot \left(\frac{\lambda \cdot l}{d} + \Sigma \zeta \right)}} \qquad (15)$$

where:

λ = friction coefficient [-]

l = length of the duct [m]

d = diameter of the duct [m]

ζ = velocity pressure factor [-]

For λ and ζ see handbooks [4] [7]

2.3. Cracks, gaps and joints

From experimental data the C values can be calculated from:

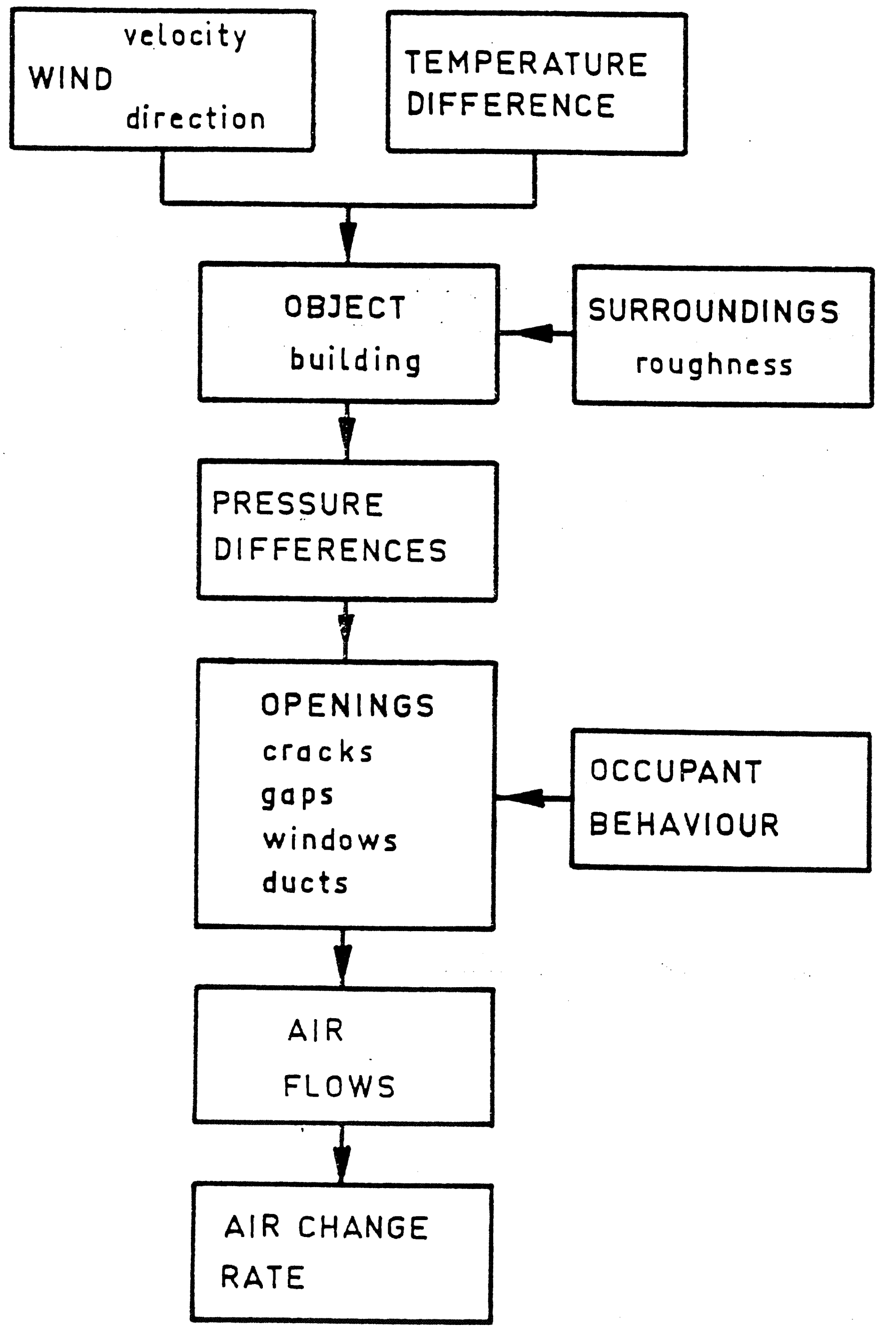
$$C = c.l \qquad (16)$$

c = specific air leakage coefficient [m^3/s . m crack length at 1 Pa]

l = length of the "cracks" [m]

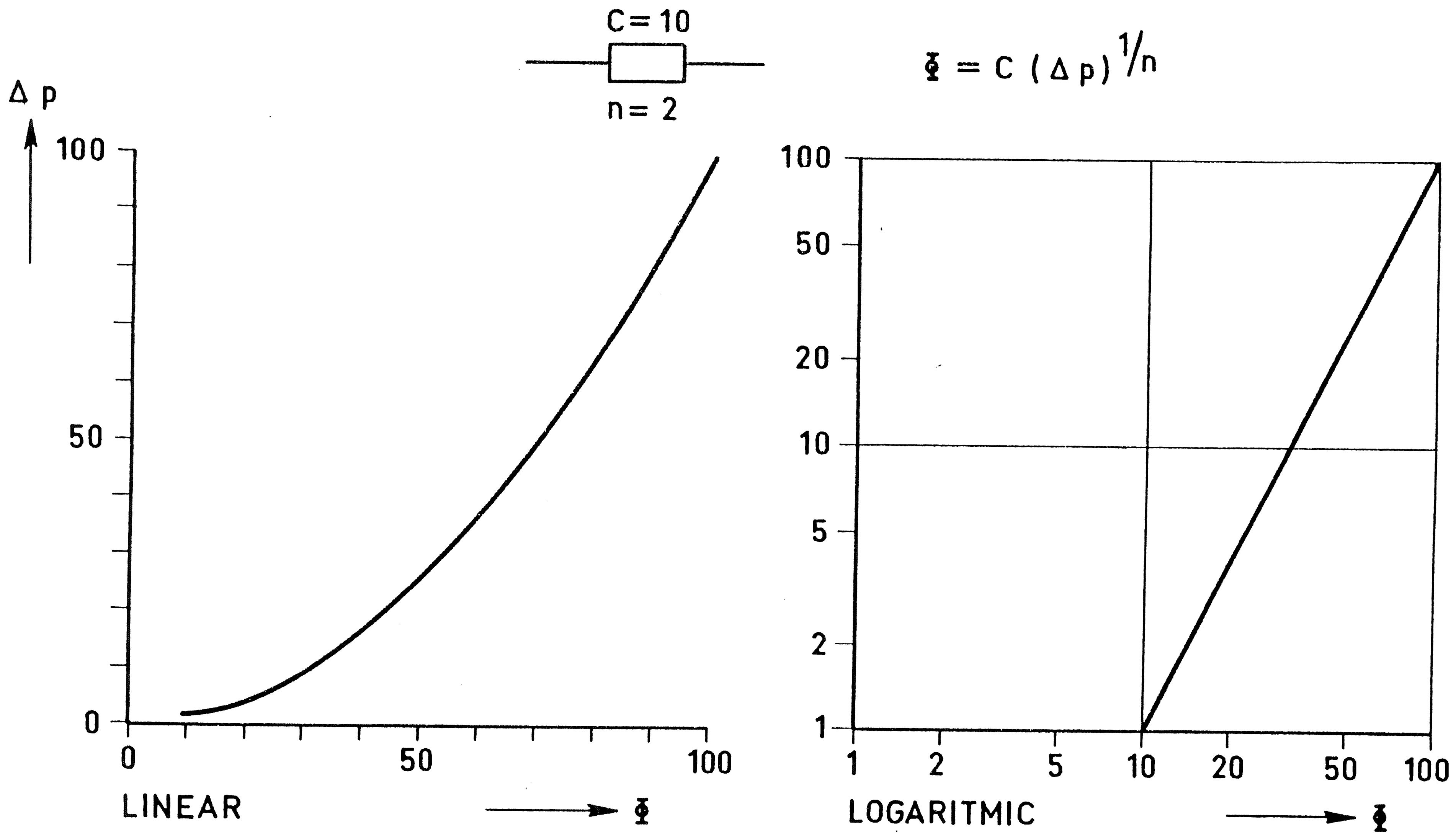
For calculations the following c values can be used.

		[m^3/s . m at 1 Pa]
window cracks	good	0,10
	moderate	0,15
	bad	0,50
doors		0,8



velocity
WIND
direction
TEMPERATURE DIFFERENCE
OBJECT
building
SURROUNDINGS
roughness
PRESSURE DIFFERENCES
OPENINGS
cracks
gaps
windows
ducts
OCCUPANT BEHAVIOUR
AIR FLOWS
AIR CHANGE RATE

FIG 1



C= 10
n= 2
Φ = C (Δ p) 1/n
Δ p
100
50
0
0
50
100
LINEAR
Φ
100
50
20
10
5
2
1
1
2
5
10
20
50
100
LOGARITMIC
Φ

FIG 2

AIR VOLUME FLOWS THROUGH A BUILDING

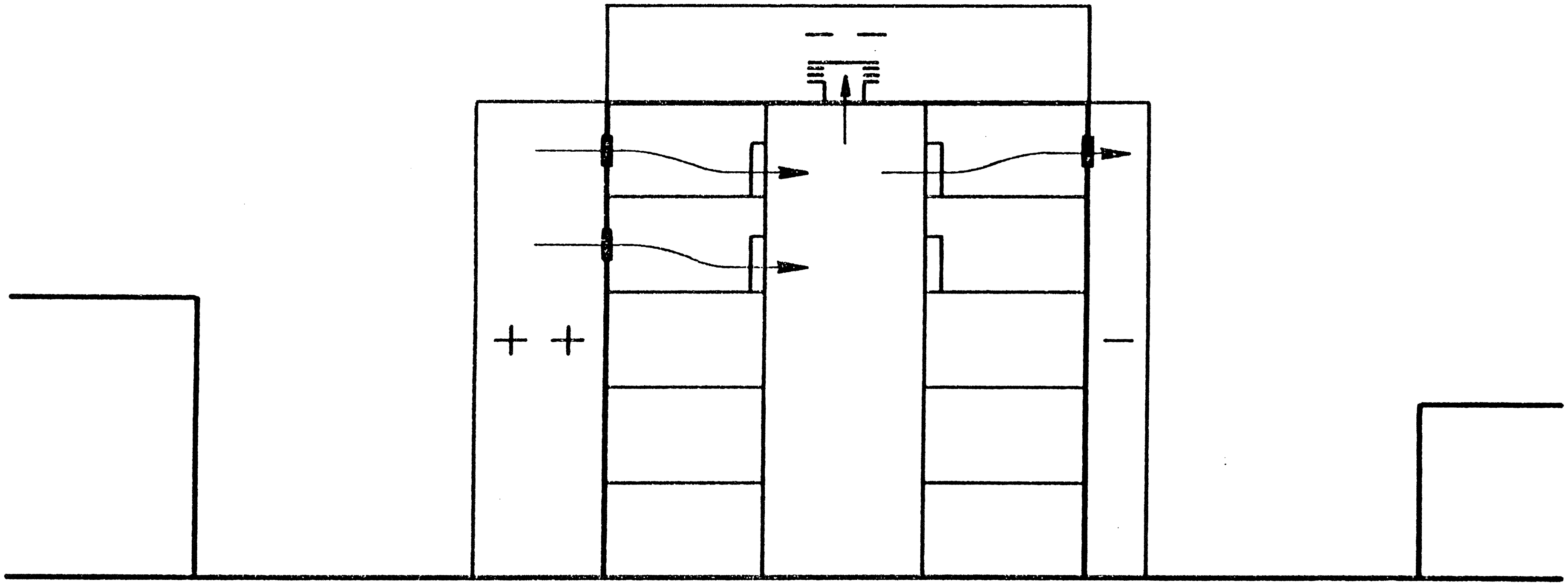


FIG 3

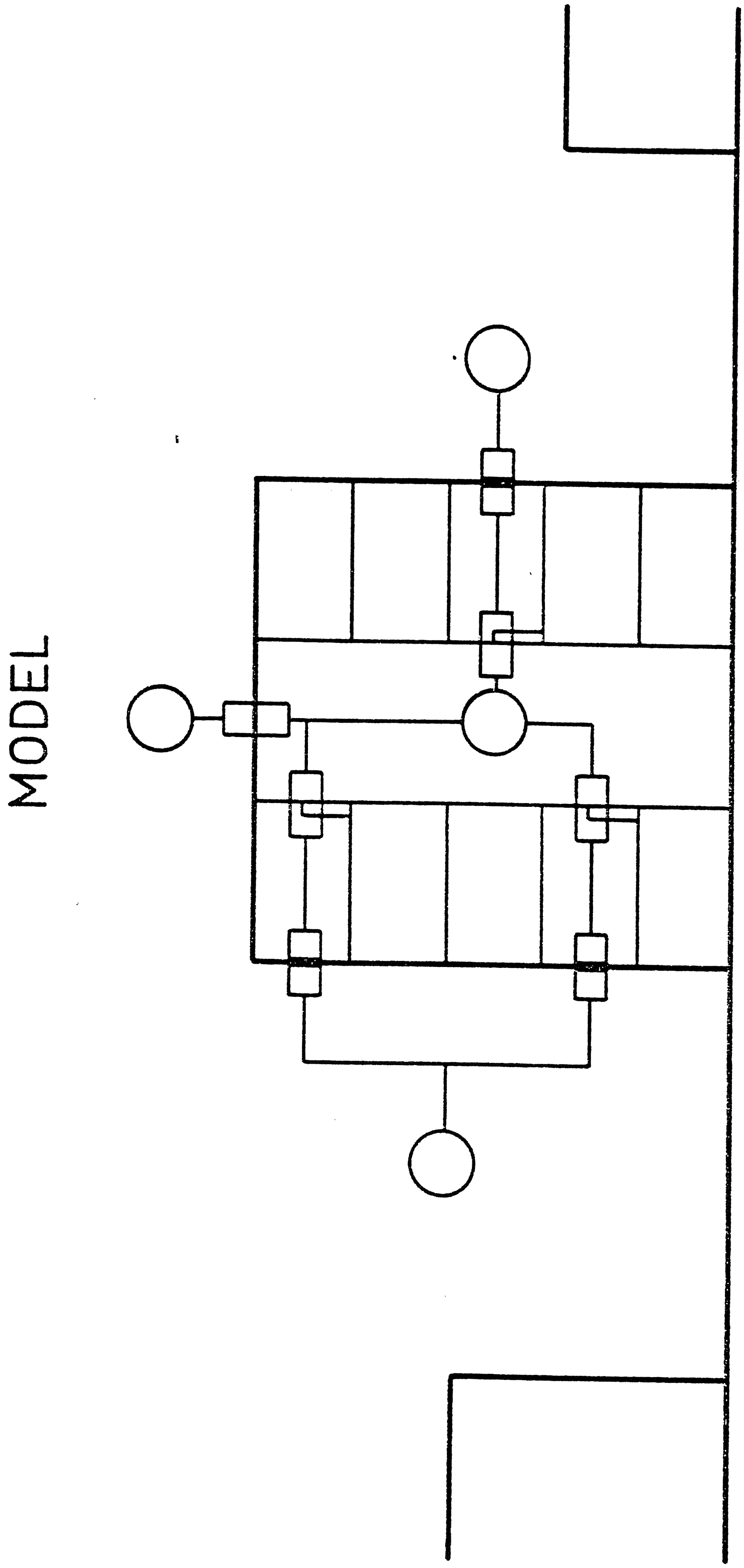
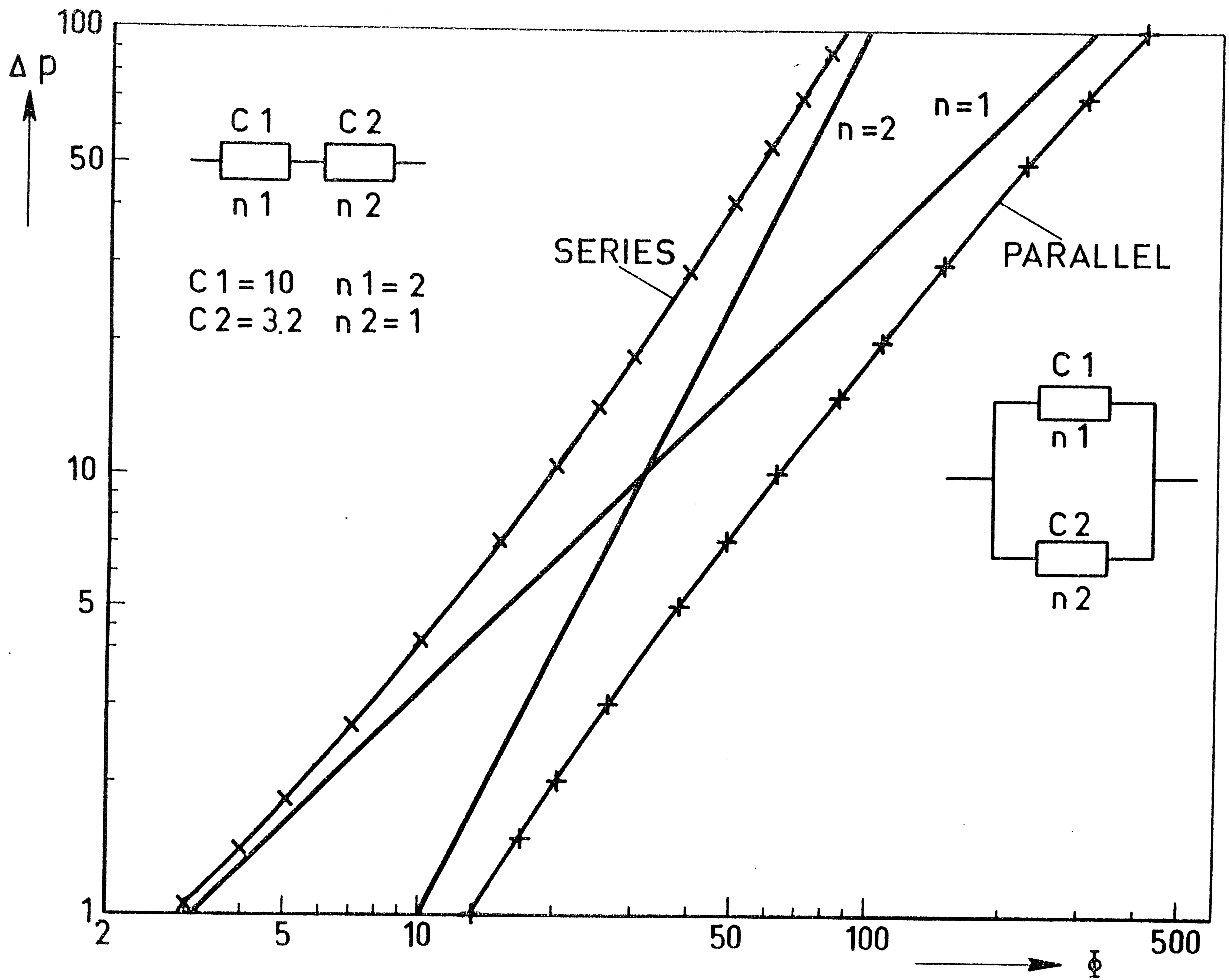
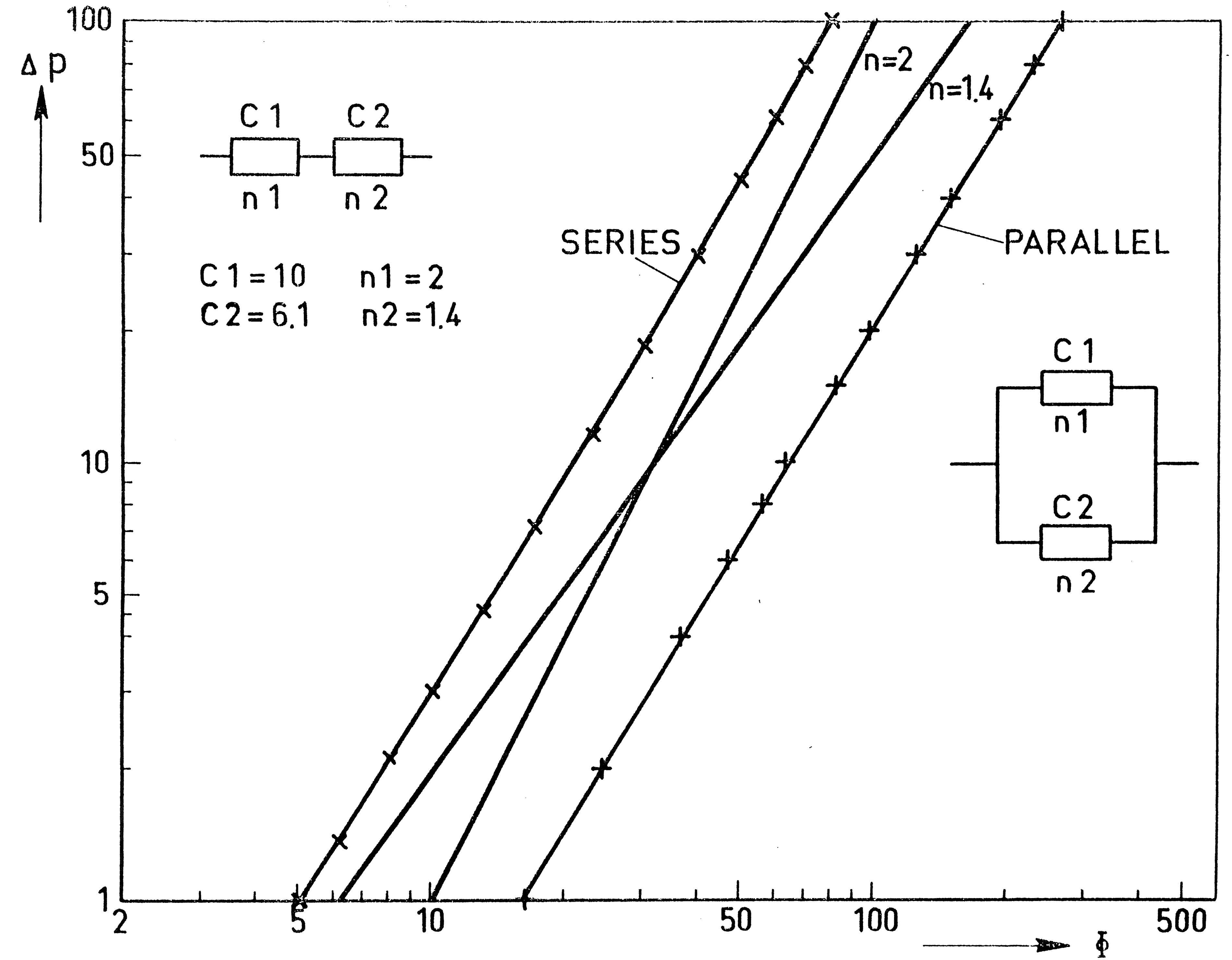


FIG 4



Δp
100
50
10
5
1
2
5
10
50
100
500
Φ
C 1
C 2
n 1
n 2
C 1 = 10
C 2 = 3,2
n 1 = 2
n 2 = 1
SERIES
n = 2
n = 1
PARALLEL

FIG 5



Δp
100
50
10
5
1
2
5
10
50
100
500
Φ
C 1
C 2
n 1
n 2
C 1 = 10
C 2 = 6.1
n1 = 2
n2 = 1.4
SERIES
PARALLEL
n=2
n=1.4

FIG 6

2 JUNCTION MODELS

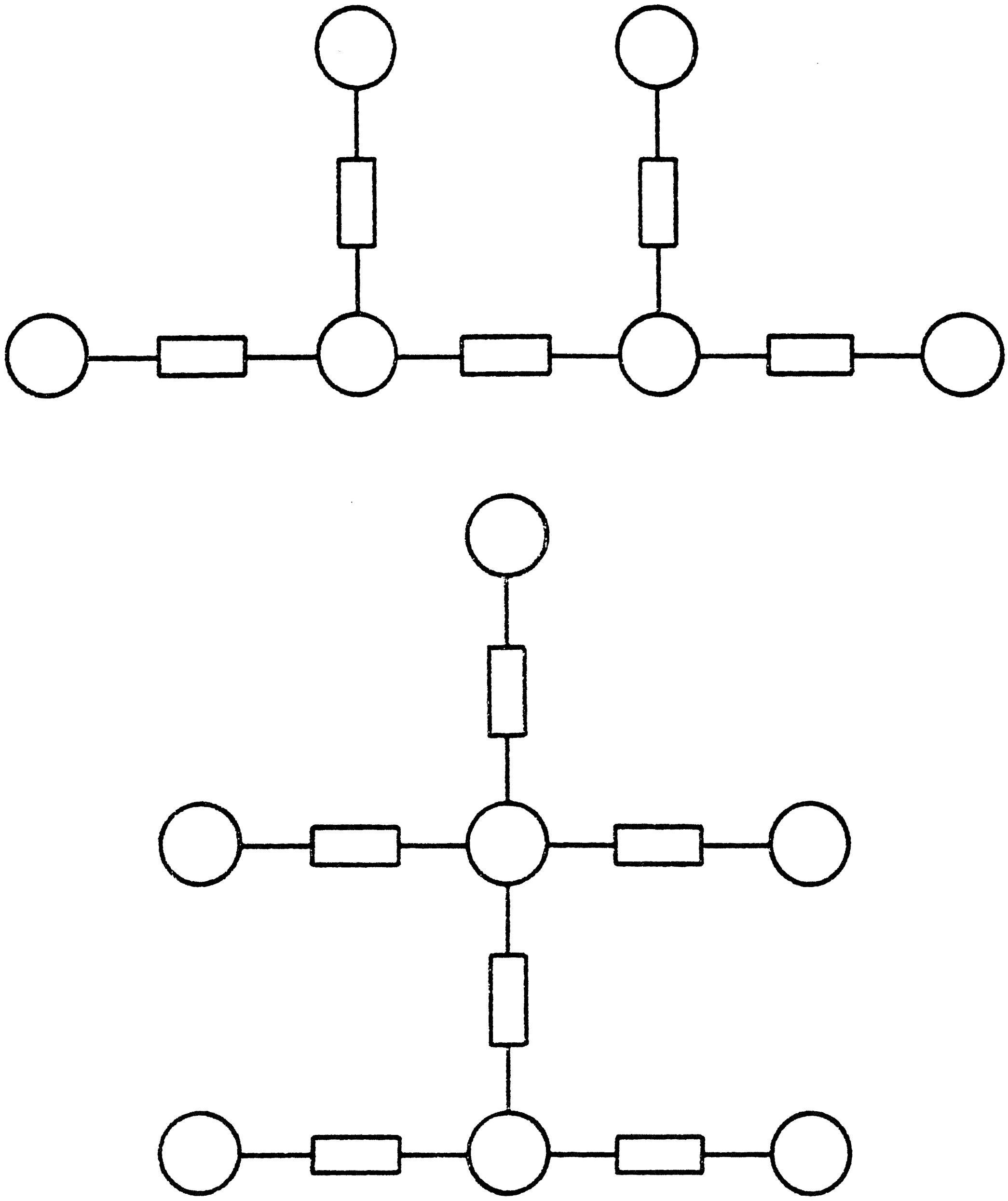


FIG 7

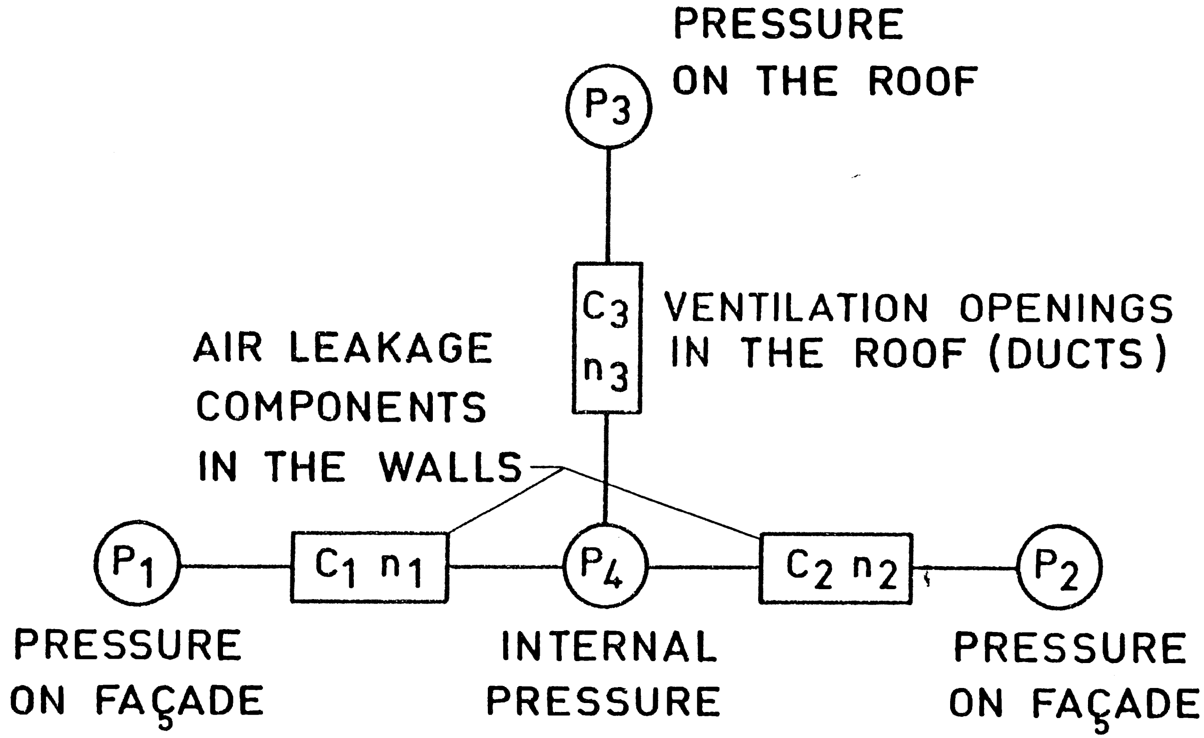
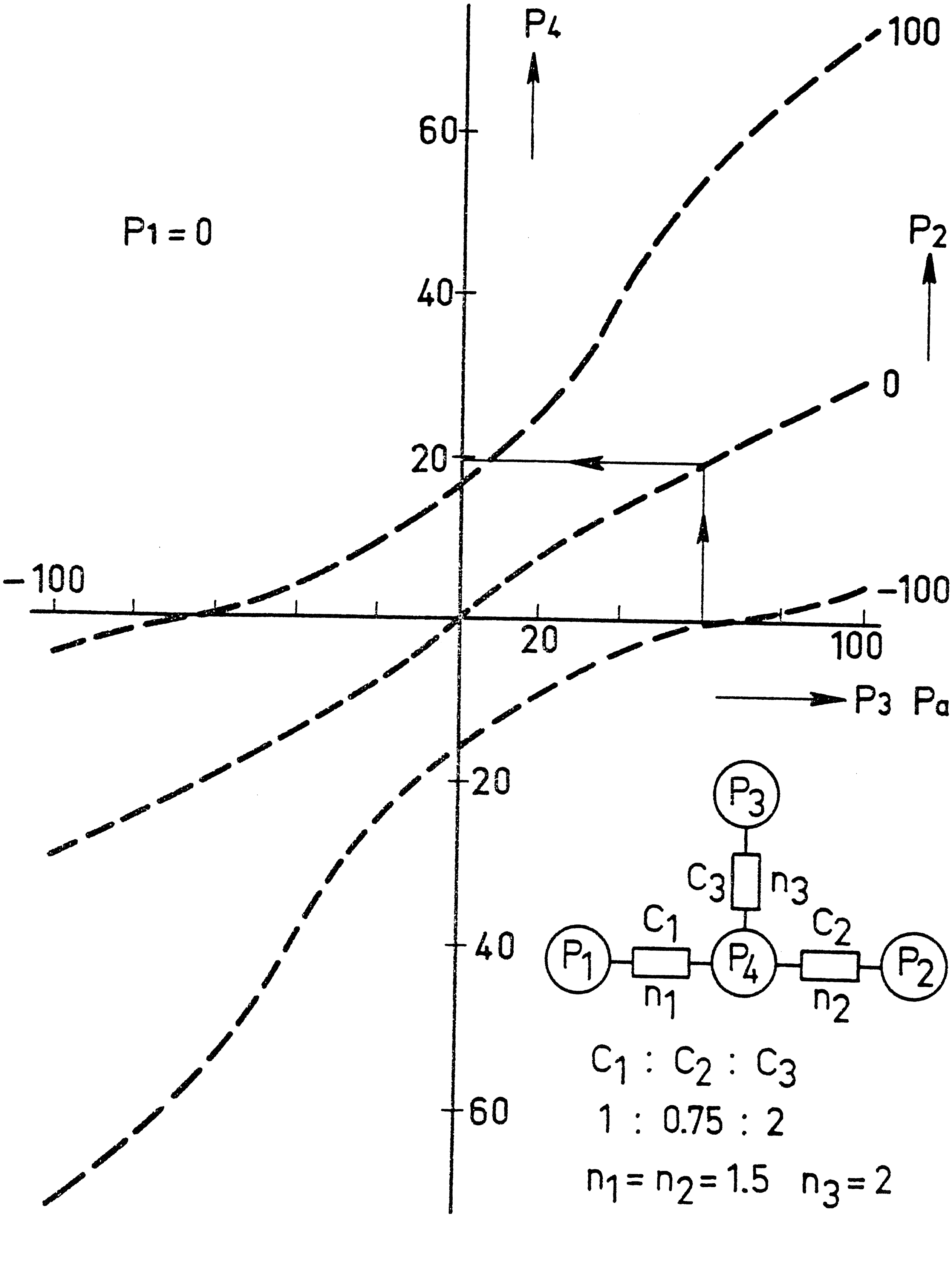

PRESSURE
ON THE ROOF
P3
C3
n3
VENTILATION OPENINGS
IN THE ROOF (DUCTS)
AIR LEAKAGE
COMPONENTS
IN THE WALLS
P1
C1 n1
P4
C2 n2
P2
PRESSURE
ON FAÇADE
INTERNAL
PRESSURE
PRESSURE
ON FAÇADE

FIG 8



P4
P1 = 0
P2
100
0
-100
60
40
20
-100
20
100
P3 Pa
20
40
60
P3
C3
n3
C1
C2
P1
P4
P2
n1
n2
C1 : C2 : C3
1 : 0.75 : 2
n1 = n2 = 1.5 n3 = 2

FIG 9

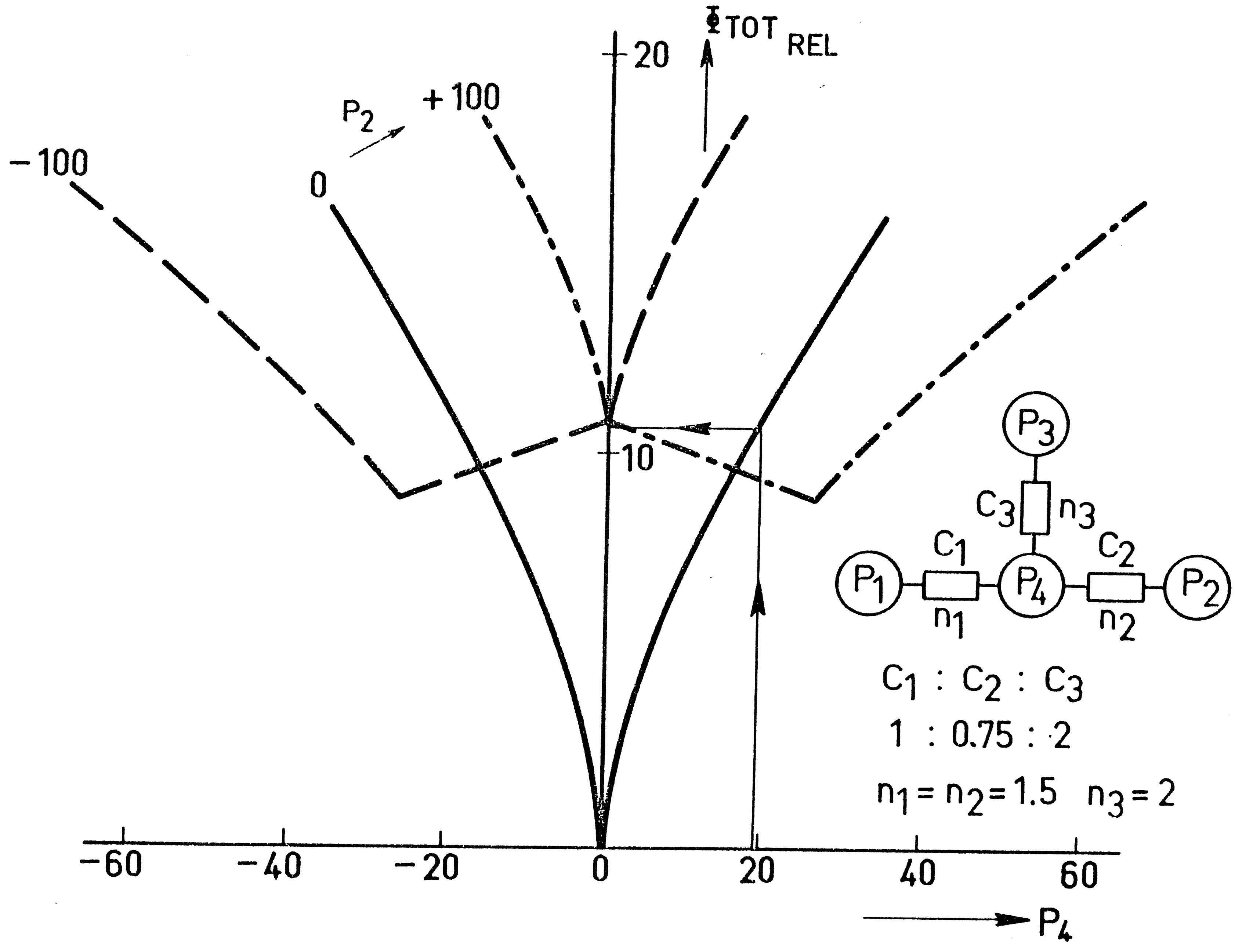

Φ TOT REL
20
10
P2
+100
0
−100
−60
−40
−20
0
20
40
60
P4
P1
P2
P3
P4
C1
C2
C3
n1
n2
n3
C1 : C2 : C3
1 : 0.75 : 2
n1 = n2 = 1.5 n3 = 2

FIG 10

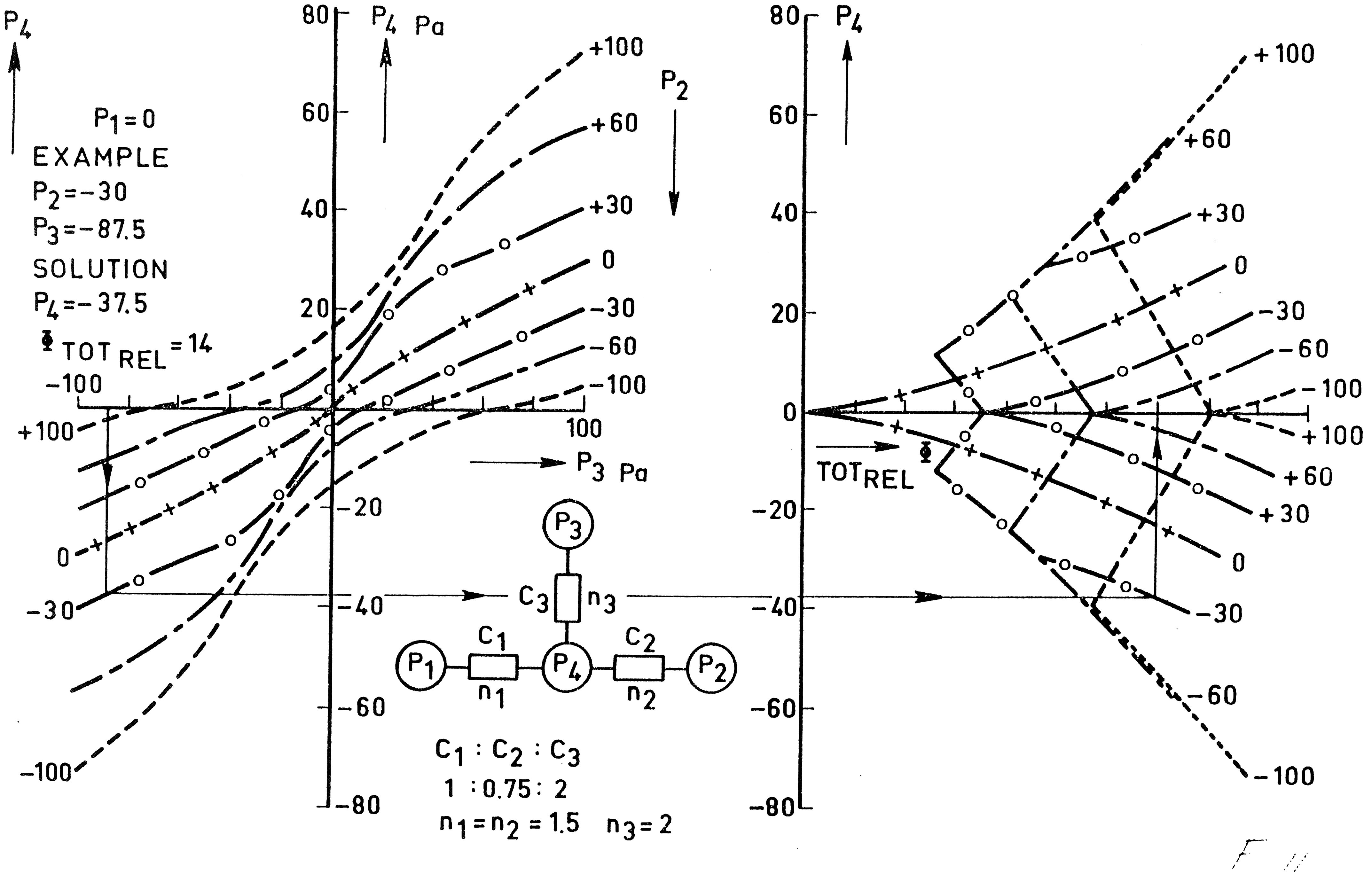
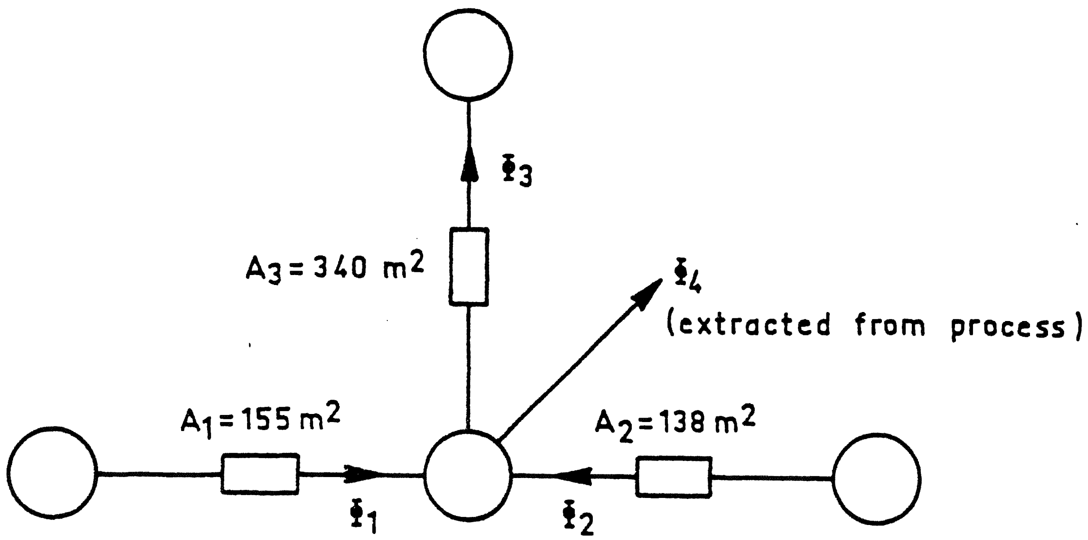

P4
P1 = 0
EXAMPLE
P2 = −30
P3 = −87.5
SOLUTION
P4 = −37.5
Φ TOT REL = 14
P4 Pa
P2
P3 Pa
+100
+60
+30
0
−30
−60
−100
80
60
40
20
−20
−40
−60
−80
100
P1
P2
P3
P4
C1
C2
C3
n1
n2
n3
C1 : C2 : C3
1 : 0.75 : 2
n1 = n2 = 1.5 n3 = 2
TOT REL

FIG 11



WIND VELOCITY ABOUT 9 m/s

WIND DIRECTION SOUTH

TEMP. DIFF. ABOUT 8 K

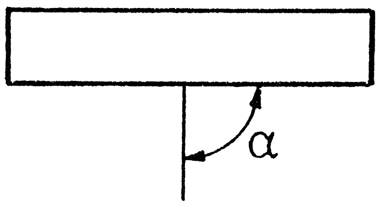
TABLE 1

MASS FLOWS BASED ON	Φ_1	Φ_2	Φ_3	Φ_4	AIR CHANGE RATE
		(kg/s)			(h^{-1})
VELOCITY MEASUREMENTS	861	50	707	133	32
PRESSURE MEASUREMENTS	807	50	694	133	34
CALCULATION MODEL	787	72	726	133	30

TABLE 2

AIR CHANGE RATE h^{-1}

DIRECTION α			90°			60°			30°		
RATIOS OF VENTILATION OPENINGS			WIND VELOCITY								
WINDWARD	LEEWARD	ROOF	2	6	10	2	6	10	2	6	10
1	1	1	33	40	64	33	39	61	33	34	52
1/2	1	1	30	32	34	30	32	32	30	31	30
1	1/2	1	31	40	60	31	38	58	30	34	50
1/2	1	1/2	19	20	33	19	20	32	19	19	27



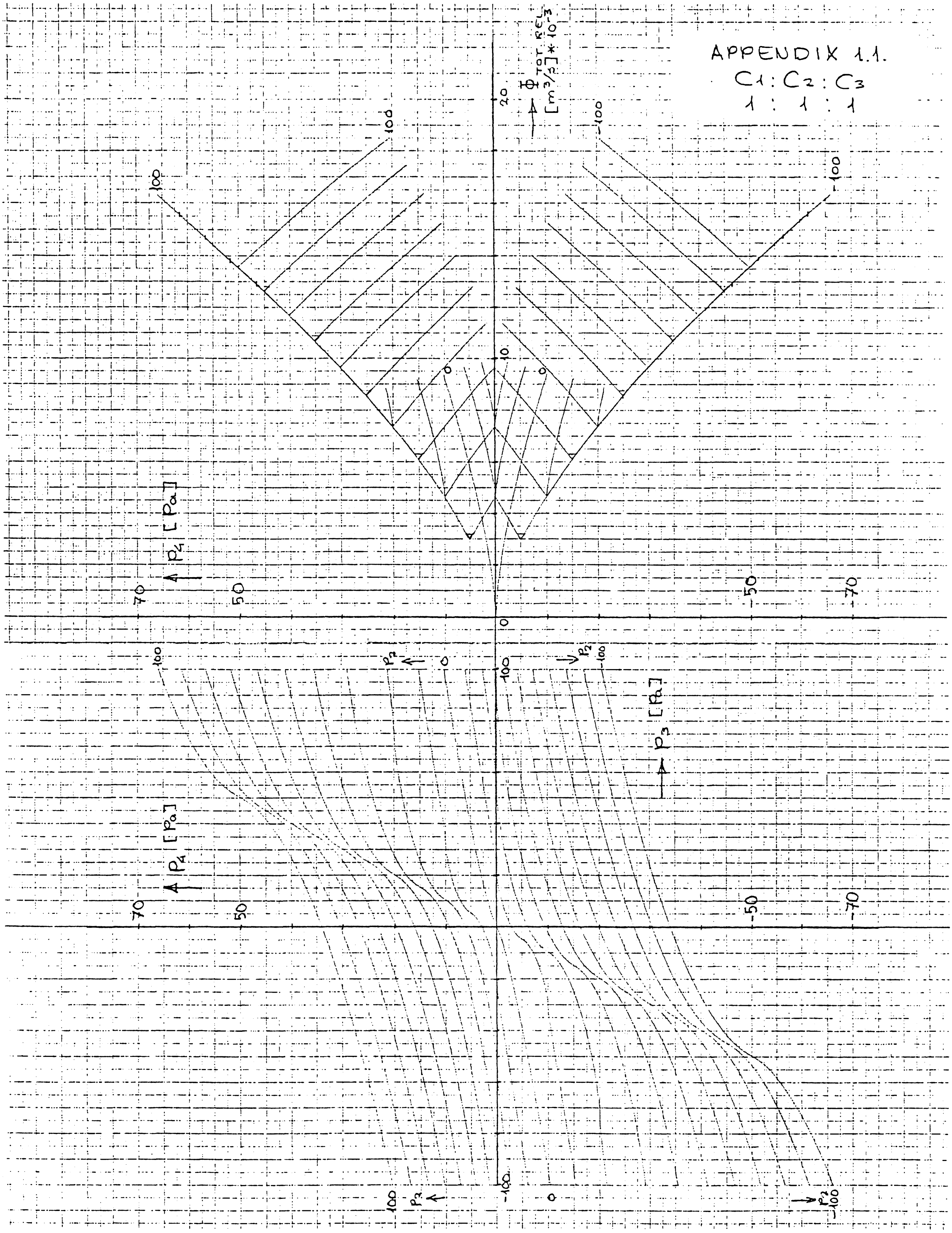
$\Delta T = 7{,}5\,K$

AIR CHANGE RATE BY THE PROCESS $= 4\,h^{-1}$

APPENDIX 1.1.

$C_1 : C_2 : C_3$

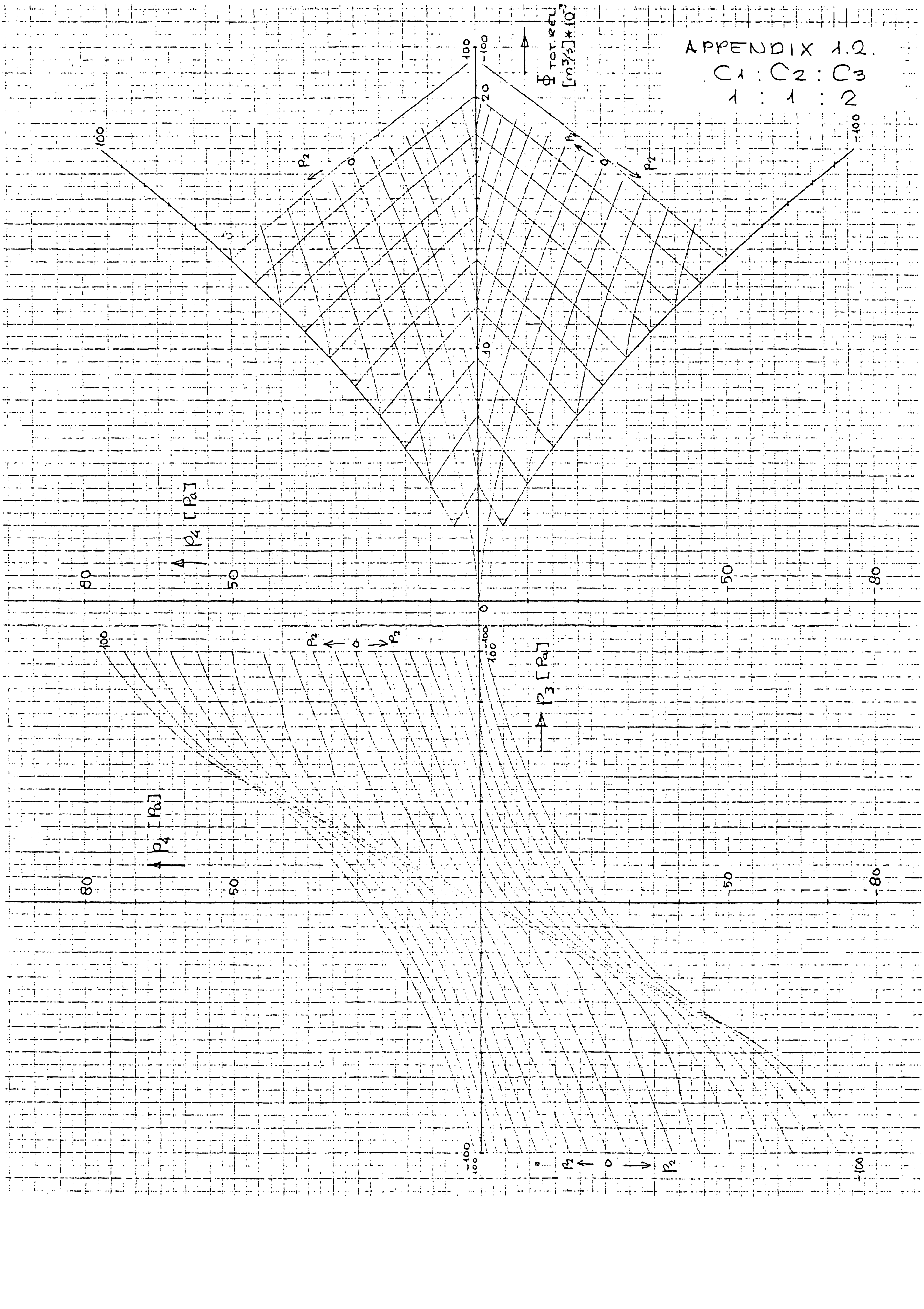
1 : 1 : 1



APPENDIX 1.2.

$C_1 : C_2 : C_3$

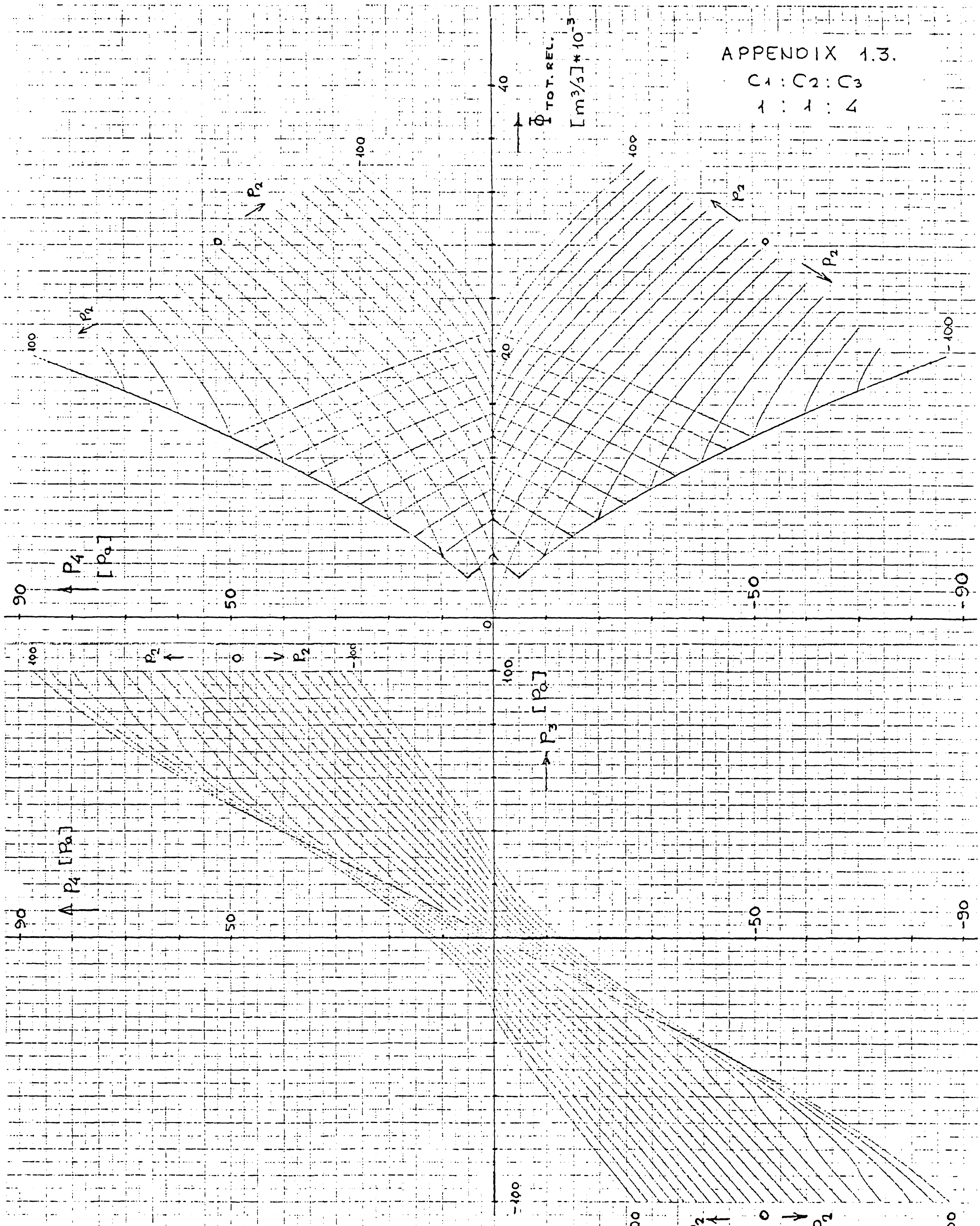
1 : 1 : 2



APPENDIX 1.3.

C1 : C2 : C3

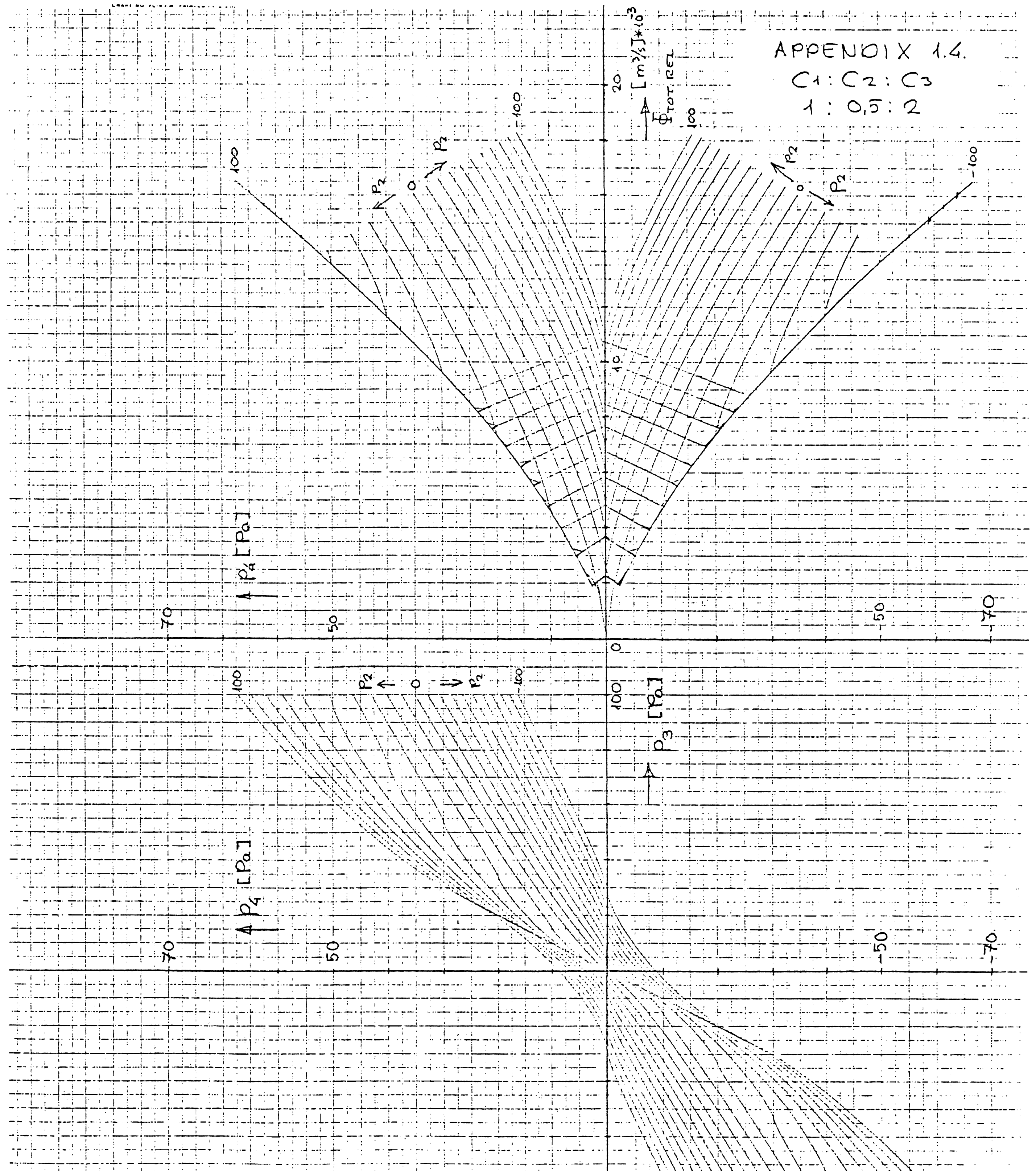
1 : 1 : 4



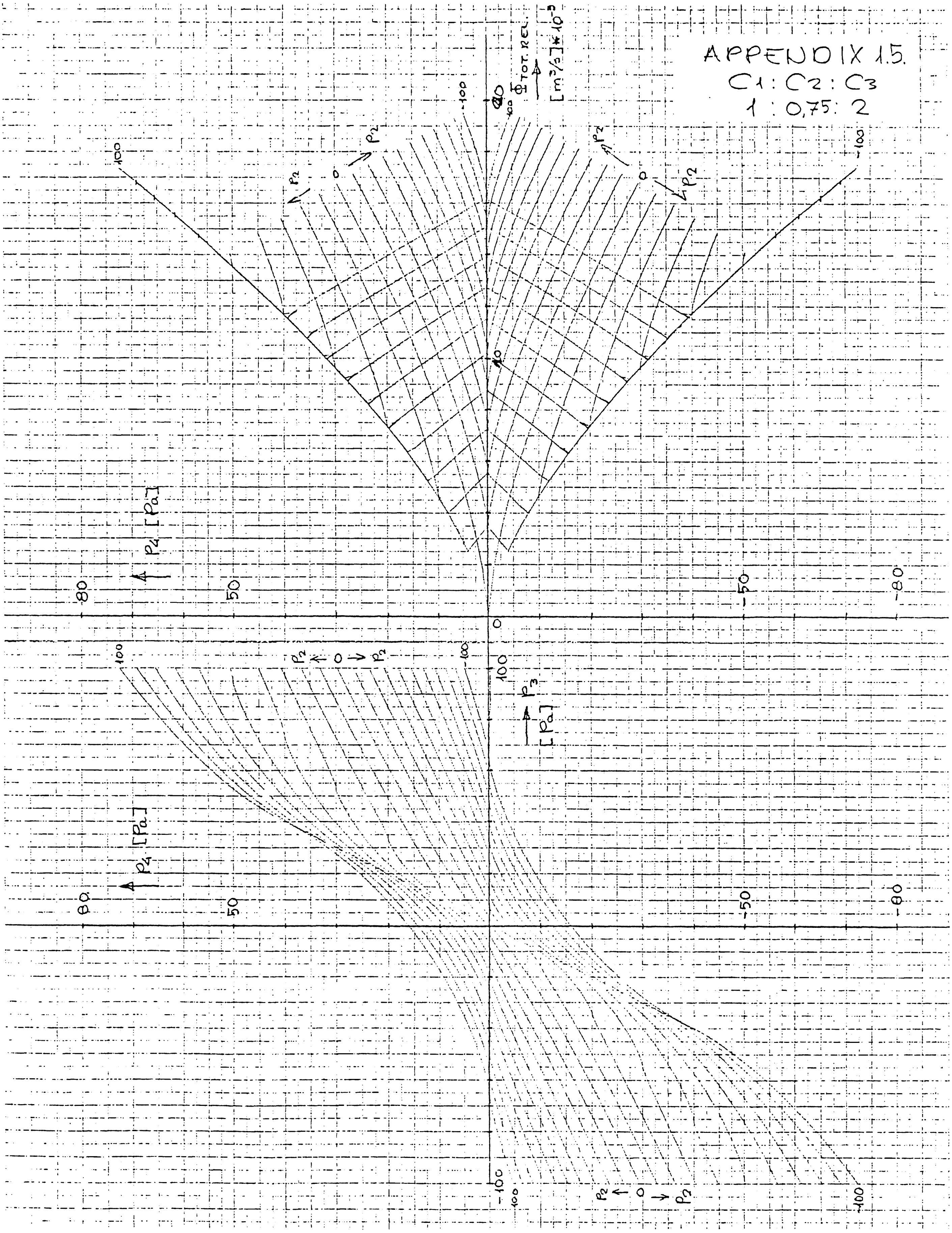
APPENDIX 1.4.

C1 : C2 : C3

1 : 0,5 : 2



APPENDIX 1.5.
C1 : C2 : C3
1 : 0,75 : 2



EFFECT OF FLUCTUATING WIND PRESSURES ON NATURAL VENTILATION RATES

I. NIGEL POTTER

INTRODUCTION

Natural Ventilation research has been continuing over many years at the Building Services Research and Information Association and started with developing computer programs to predict natural ventilation rates in buildings. The earlier work concentrated on predicting the natural ventilation performance of large hospitals whilst they were still at the design stage.

The Association was, more recently, involved in a contract from the Building Research Establishment to measure the natural ventilation performance of fourteen modern domestic dwellings in England and Wales. The air change rates, temperatures, wind speed and directions, air leakage characteristics of windows, doors and rooms were measured in each house for, on average, five week periods. If the air leakage characteristics of the windows and doors were used in the computer model the correlation between measured and predicted ventilation rates was not as good as may be expected. One major source of error was the large 'background' air leakage characteristic of the building shell.

This background leakage was measured in some of the test houses by the Building Research Establishment but this does not provide data on where the air paths go to, which is a necessary input to the computer model. However, computer predictions taking account of the background leakage of the shell still did not give an adequate correlation with measured values[1].

(NB The air paths were approximately identified from the air leakage of the individual rooms and the whole house. Some proportioning was necessary to take account of air leakage paths between rooms other than via doors, hatches, etc.)

It was subsequently decided to investigate the dynamics of natural ventilation, at least for a simple case, with support from the Department of Health and Social Security for laboratory trials and from the Building Research Establishment for the site trials, on which this paper is based.

In the computer model the wind pressures acting on the building are assumed to be steady and are normally derived from time averaged pressures acting on a wind tunnel model.

The purpose of this research was, therefore, to quantify the difference between actual dynamic ventilation rates and the natural ventilation rates which would be predicted using a steady state model.

Tests were conducted in a single room with windows in opposite walls. The test room was located on the first floor of a three-story dwelling situated on a new housing estate in Bracknell.

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This paper details current steady state prediction procedures, the new techniques developed for dynamic natural ventilation rate measurement and the analysis procedures. Comparisons are made of predicted and actual ventilation rates along with attempts to correlate differences as a function of wind speeds, wind directions, flow reversal, etc.

Even though the scope of this project was limited, indications are that significant under-estimates of the ventilation rates are incurred by assuming a steady state prediction model.

CURRENT STEADY/STATE PREDICTION METHODS

The BSRIA developed CRKFLO program [(2)] represents a 'steady state' procedure for the prediction of natural ventilation rates in buildings. Data required for the procedures consist of room volumes, mechanical ventilation rates, air leakage characteristics of the components and predicted steady state pressures due to stack effect and wind.

The wind pressures are normally derived from measurements made using wind tunnel models. With the model set at various orientations to the air flow, pressure measurements are made at selected points on the surface of the building model. These measured pressures are normally time-averaged and the corresponding pressure coefficients calculated using the equation

$$Cp = \frac{\overline{P}x}{\overline{P}v}$$

where

Cp = wind pressure coefficient

$\overline{P}x$ = time-averaged pressure

$\overline{P}v$ = time-averaged velocity pressure at reference height in free air stream

Using the Cp values the wind pressure at the corresponding location on the real building can be predicted for the relevant wind direction and any selected wind speed. The wind pressures so derived are used in calculation of ventilation rates on the assumption that they remain steady at the predicted values.

However, in reality the wind pressures on a building are continuously varying. These variations are caused by locally generated turbulence and by overall changes in wind velocity. There are many parameters which are likely to generate or affect the surface pressure variations including the building size and shape, nearby buildings and topographical features and the type of terrain over which the wind has passed.

The way in which these complex pressure variations will influence the natural ventilation process is difficult to predict. Considering the following simple example, it is evident that the effect is likely to be significant.

The example chosen is a rectangular plan building with one opening centrally located in each of two opposite sides. When the wind direction is parallel to the faces of the building which contain the opening, it would be expected that the time-averaged pressures on these faces would be negative and of the same magnitude. Thus the average pressure difference across the two openings would be zero and hence the net predicted ventilation rate would also be zero. In fact the surface pressures would be fluctuating and instantaneous pressure differences would result, thus producing a ventilation rate. This effect was illustrated by the British Gas Research on full-scale and wind tunnel model tests in a Portakabin (Ref.3). The ventilation rates measured with tangential wind directions were only just under half the rate at normal wind directions.

DESCRIPTION OF TEST HOUSE

A three-story house in Bracknell was chosen because it contained a through room with an openable window in opposite walls of the house. This room could be sealed from the rest of the house and thus be treated as a simple naturally ventilated enclosure.

The house was situated on the edge of a housing estate with some open land and a road to the south with woodland beyond. The surrounding houses are shown on the right of Fig.3.

The block of houses including the test house was on slightly higher ground than those to the north. A five foot high wall surrounded the small gardens to the south of the housing block.

The test room was situated on the first floor and would normally be used as a lounge. The openable windows were top-hung wooden framed. There were also three fixed windows to the rear of the house and one small fixed window at the front.

The central heating was gas fired serving radiators. The test room contained two radiators and the thermostat, thus providing temperature control in the test room.

MEASUREMENT OF AIR LEAKAGE CHARACTERISTICS

In a real building air infiltration takes place not only through gaps around windows and doors, but also through cladding components, cracks in the walls and ceiling and even through electrical conduits and around central heating pipes. For this research it was necessary to take account of all the air leakage paths in the test room. For practical reasons, it was only possible to study the air leakage through the openable windows so all of the other leakage paths were sealed using plastic sheeting, adhesive tape and various fillers as appropriate. The air tightness of the room was measured by the pressurisation technique with the windows sealed off.

The air leakage characteristics of the openable windows were measured by taping plastic sheet around the window to form a sealed shroud. Air was extracted or supplied to the shroud and the pressure difference across the window was measured with an electronic micromanometer. Depending on its magnitude, the air flow rate was measured using either a calibrated nozzle or a laminar flow element. Graphs were then plotted of pressure difference versus air flow rate and thus the characteristic constants, K and n were calculated for both windows and for both inward and outward air flow.

PRESSURE MEASUREMENT

The pressures measured on a wind tunnel model are pressure differences between the particular surface and the free stream static pressure. On site it is impossible to measure pressures with respect to the external free stream static pressure. The alternative of setting up a reference invariant static pressure source is also very difficult. Hence only local pressure differences can be accurately measured.

However, such measurements can readily be related to predicted values by considering the algebraic sum of pressure coefficients at the relevant building surfaces.

Thus for comparative purposes the pressure difference across the whole house was measured together with the pressure differences across the individual windows.

The external pressures were sensed through four pressure tappings drilled into each window pane and connected by tubing to a manifold. The pressure differentials were measured with sensitive electronic micromanometers, the output signals from which were transmitted to an analogue tape recorder.

MEASUREMENT OF AIR FLOW RATES

Air Change Rate Measurement

The air change rate was measured by monitoring the decay in concentration of N_2O, previously injected into the test room. The concentration was measured with an infra-red gas analyser and the output signal was recorded on a chart recorder.

Twelve sampling points were equally spaced in the test room and connected by tubing to a manifold and then to the analyser, thus ensuring a representative sample of the room air. Four small fans were also installed in the test room to provide adequate mixing of the test room air/tracer gas mixture. It had been found in the laboratory that these two precautions enabled consistently accurate results to be achieved.

The theoretical decay of concentration is related exponentially and is represented by

$$Cf = Ci \cdot e^{-Nt}$$

where

Cf = final concentration, ppm

Ci = initial concentration, ppm

N = air change rate, hr^{-1}

t = elapsed time, hr

The air change rate derived from the concentration decay measurement was then used calculate the time-averaged flow rate, Qm, through the test room.

Flow Rate From Power Law Converted Pressures

Air change rate measurements do not provide information on the direction of flow throu the windows. It was therefore, necessary to devise a method for quantifying the vector of flow rate and direction. During each test period the pressure difference across the windo was continuously monitored. The air leakage characteristic was known and obeyed the relat $Q = K\,(\Delta P)^{1/n}$, down to very low flow rates. An electronic instrument was developed which would raise continuously the measured pressure difference to the power $^1/n$, thus providing an output linearly proportional to flow rate.

The device has been called a power law converter (P.L.C), and the exponent n may be adjusted to any value between 1 and 2. When the pressure difference goes negative (i.e., the direction of flow changes) the correct negative flow rate was also output. Thus integration of the positive and negative output components produced time averaged flow rates, $\pm Q_{P.L.C,}$ over the specific test period.

The total inflow Q_{IN} into the test room was then calculated from the inflow component of the back window $Q_{P.L.C.b}$ plus the inflow component of the front window, $Q_{P.L.C.f}$. Similarly the time averaged out-flow rate, Q_{OUT}, was calculated.

Flow Rates Derived From Averaged Pressures

The pressure difference across each window and the house were integrated over the test period and the average pressures calculated. These pressures are representative of the steady state model. From these pressures the corresponding flow rates were derived from the back window, $Q_{\Delta\bar{P}b}$, the front window, $Q_{\Delta\bar{P}f}$ and across the house $Q_{\Delta\bar{P}h}$. These flow rates are analagous to the steady state predicted air flow rates.

ANCILLARY MEASUREMENTS

The wind speed and direction were measured with an anemometer and windvane mounted on a 10 m telescopic mast situated in the back garden of the house. The wind speed and direction were recorded on an anemograph. To allow detailed analysis, the wind speed was also recorded on an analogue tape recorder.

Temperatures were measured with shielded copper-constantan thermocouples and recorded automatically. The external temperature was measured with the thermocouple placed inside a Stevenson screen, situated in the back garden.

Hence all measurements were recorded either on an analogue fourteen-channel magnetic tape recorder or on chart recorders. The data records were analysed in the laboratory.

ANALYSIS PROCEDURE

Sixty tests were conducted with pressure traces and were approximately of one hours duration although a further forty tests were conducted to measure ventilation rates, windspeeds and temperatures only. However, not all of the data was analysed.

The data tapes were processed using analysis instrumentation consisting of a 14-channel tape recorder (similar to the unit on site), digital voltmeters for calibration purposes, three digital integrators, the Power law converter and a U.V. recorder. There was also a frequency spectrum analyser system consisting of a correlator and spectrum display module.

Data retrieved when the tapes were processed consisted of:

1. Integration of pressure differences across the front and back window over the test period.

2. Integration of pressure differences across the house over the test period.

3. Integration of positive and negative flow rates from P.L.C. through the front window.

4. Integration of positive and negative flow rates from P.L.C. through the back window.

5. Integration of wind speed over test period.

In the case of 3 and 4 the P.L.C. was linked between the tape channel output and the integrators.

The tape playback amplifier cards were calibrated before each run. For a window flow integration, two normally zeroed integrators were used, one for positive and one for negative flow rates. For a window or house pressure difference integration, one half scale zeroed integrator was used. Thus the half scale zeroed integrator covered the full positive and full negative pressure range. Correction for the offset was made. The windspeed integration was used to give an average of the windspeed over the test period.

RESULTS

Measured Tracer Gas Ventilation Rates as a Function of Wind Speed and Direction

A plot of results of the air change rate measurements against wind speed is shown on Fig.1. There is an evident trend of higher ventilation rates at the high wind speeds but other factors such as wind direction and indoor to outdoor temperature differences give rise to the significant scatter of points.

The effect of indoor to outdoor temperature differences will be much more pronounced at low wind speeds so to assess the directional effects a polar plot has been made of those results at wind speeds above 2.5 m/s (Fig.2). For this plot the measured ventilation rate has been divided by the wind speed because this ratio may be expected to be constant at any given wind direction based on the steady state flow characteristics of the test room windows, (since flow rate through the windows was approximately proportional to the square root of the pressure difference and the pressure difference is proportional to the square of the wind speed, the flow rate divided by wind speed should be constant in the absence of stack effect for a given wind direction). Using classical steady state predictions (see section on Current Steady State Prediction Methods) the ventilation rates at 70° and 250° (parallel to window surfaces) would be expected to be zero, while normal wind directions would yield high ventilation rates.

It is evident from Fig.2 however, that the measured ventilation rates show no clear dependence on wind direction, although it may be concluded that the ventilation rates are somewhat lower for wind directions near 70° and 250°; i.e., winds approaching the window/walls at tangential angles. It is also noted that the ventilation rate is much higher with a wind direction about 250° than at 70°; it is thought that this was due to the sheltering effect of other groups of houses to the east of the test house and the catchment effect on southwesterly winds of the wall of the adjacent house.

Other factors which reduce the directional effects include the variation of direction about the mean and the fluctuations of pressure which give rise to flow oscillation.

Comparison of Flow Rates Derived From Power Law Converter Analysis and Those Measured by the Tracer Gas Technique

The agreement between the flowrates in and out of the test room derived from the power law converter analysis of the pressure differential recordings was generally good.

Discrepancies in the inflow and outflow were assumed to be due to instrument error, and where the values did not agree to within 10% these test results were discounted, although other physical factors may be responsible and will be discussed later.

The mean of the inflow and outflow from the P.L.C. was taken to be ventilation rate in litres per second. It is called the dynamic determination of the ventilation rate. The relationship between this dynamic determination and the rates obtained from the tracer gas measurements is shown in Fig.3.

There is fairly good agreement between the two sets of data although expressed in percentage terms the errors are much higher at low ventilation rates; i.e., less than 9 l/s ≡ 0.66 air changes/hr. In the majority of tests the dynamic determination of ventilation rate was lower than the rate measured by the tracer gas technique.

However some discrepancies will arise between the dynamic determination of the ventilation rate and the measured values because the pressure distribution around the entire crack length is assumed to be uniform in the dynamic determination. Especially at low flow rates, stack effect will modify the vertical pressure distribution and give rise to the high discrepancies at low flow rates. Secondly the pressure at the crack itself may be slightly different from the pressure measured at the window pane. This difference would be expected to be prominent at tangential wind directions since the frame protrudes out from the glass. There is in fact a fair correlation between the percentage difference between the measured ventilation rate and the dynamic determination as a function of wind direction, as illustrated in Fig.4.

Finally, discrepancies may occur because the window crack has a finite length and not all the air which is indicated as a flowrate by the P.L.C. actually penetrates into the room. This effect may predominate in high flow reversal conditions in which the dynamic determination may be higher than the measured flow rate.

<u>Comparison of Flow Rates Derived From the Power Law Converter Analysis and Time Averaged Pressure</u>

This comparison is fundamental to the dynamics of natural ventilation. The same pressure recording on the tape was analysed in two different ways. The time averaged pressure was derived and is analagous to a wind tunnel average pressure recording. This steady state pressure was then converted into a flow rate. This was then compared with the dynamic determination of the ventilation rate using the power law converter.

The comparisons of these two derived flow rates are given in Fig.5 for the front and back windows. The percentage error between the time averaged pressure flow rate was between 20 - 30% less than the dynamic prediction method for high flow rates and up to ∿ 80% during low flow rate conditions.

This highlights the magnitudes of the potential errors involved in using the present steady state prediction methods.

<u>Ventilation of the Whole Room Compared With Current 'Steady State' Predictions</u>

As outlined previously the current prediction method is based on the assumption of steady time-averaged pressures and a knowledge of the air leakage/pressure characteristics of windows and doors etc.

This method was applied to the present tests by deriving the mean pressure difference across the house over the test period and using that value in determining the leakage through the two windows in series based on their measured leakage characteristics.

These steady state predictions were compared with the measured ventilation rates (tracer gas technique) and the resulting error plot is shown on Fig.6. This indicates that the measured values were always (with just one exception) higher than the predicted values, by about 25% at flow rates above 10 l/s and rising to nearly 80% at lower flow rates. This again highlights the degree of underestimation resulting from the current prediction method.

Effect of Flow Reversal

The flow through the window cracks did not remain in the same direction for the duration of any tests. This flow reversal occurs because of the dynamic behaviour of the wind near the house as previously discussed. The output from the P.L.C indicated the direction of flow by its sign (-ve or +ve).

For each window the percentage flow reversal was calculated and was expressed as the time averaged flow in one direction as a percentage of the total flow (negative plus positive) and therefore yields a value between 0 and 50%.

Fig.7 is a plot of the percentage flow reversal as a function of the percentage error between the flow derived from the P.L.C, $Q_{P.L.C}$ and the steady state flow rate calculated from the time averaged pressure differences. As expected, the greater the degree of flow reversal the higher the errors. However, it was expected from laboratory trials that errors of only ∿ 10% should occur at low flow reversal conditions. In fact errors ∿ 20 - 30% are apparent at low flow reversal conditions.

Considering again a simple symmetrical building with openings in opposite walls, the highest degree of flow reversal would be expected at wind directions parallel to those walls. At perpendicular wind directions little or no flow reversal would be expected.

The directional dependence of flow reversal in the present tests is shown in Fig.8. These indicate that greater flow reversal did occur at near parallel wind directions but there are also some low values at the same directions. These latter results were for average to high wind speeds and were associated with high ventilation rates. There was insufficient test data to pursue an analysis of the dependence of the degree of flow reversal on wind speed at given wind directions.

Influence of Stack Effect

A temperature difference between the inside and outside of the house will produce a ventilation rate due to the stack effect. If the inside of the room is at a higher temperature than the outside, air will tend to leave the room at the upper edge of the windows and enter through the lower edge. The converse is true for a room temperature below that of the outside air. Thus there will be a stack pressure across the window gap which will vary in magnitude and sign from the top to the bottom of the window.

Assuming steady state conditions, the ventilation flowrate due to stack effect can be calculated if the window dimensions, internal and external temperatures and wind pressures are known. A dynamic analysis would have to be made to ascertain the true contribution in practice because of the fluctuating wind pressure. Such an analysis is beyond the scope of the present studies. However some steady state calculations were made using mean wind pressure values and from the results of these it is evident that the stack effect will contribute significantly to the error between predicted and tracer gas ventilation rates when the flowrate is low, but not at high flowrates.

It is important to bear in mind that if fluctuating flows had been considered for the whole house the relative importance of stack effect would have become more dominant since stack effect is a function of the vertical height between openings.

CONCLUSIONS

The relationship between the measured air change rates and wind speed broadly followed the theoretically expected trend. For wind speeds greater than 2.5 m/s the stack effect was expected to be minimal and at the higher wind speeds the ratio of ventilation rate divided by wind speed did have some slight direction dependence. The lower values corresponded to wind approaching the windows/walls at tangential directions from the North East and South West. The tangential wind directions however do indicate relatively high ventilation rates and it would be useful to compare these results with predicted ventilation rates using pressure data derived from wind tunnel model tests.

The power law converter developed for this project generally worked well. It was hoped that good agreement of the P.L.C. flow rates and tracer gas measured flow rates could be achieved and in fact were always within 2.5 l/s. However at low flow rates this does represent a significant error and could easily be due to the pressure gradient up the window generated by stack effect, non-uniformity of the pressure round the entire crack length and at flow rates below 1.5 l/s, the characteristic constants K and n are no longer accurate. The tracer gas measurement technique itself may be responsible for some of the discrepancy.

Comparing the flow rates predicted from the time-averaged pressure differences across the windows with either the tracer gas derived flow rates or the P.L.C derived flow rates significant errors were found. Indeed they nearly always exceeded 20% and rose to 80 + % at the lower flow rates (Fig.5). These results identify an error in the present steady state prediction procedures. Although these results apply to a single room in a house, the significance of the dynamic aspect of natural ventilation mechanics is evidently important and warrants further investigation to extend the scope to complete buildings.

Some attempt was made to correlate the errors with parameters such as percentage flow reversal. It is interesting to note here that the direction of flow did not remain constant for any test even at normal wind directions. The percentage error between the steady state predicted flow rate and the measured flow rate does, as expected increase with a greater percentage flow reversal. However, even at low flow reversal conditions the errors are still around 25%. It is difficult to explain this since laboratory trials with fluctuating flows but in a constant direction, rarely exceeded an error of 10%. Obviously the wind could not be accurately modelled in the laboratory and may be responsible for the apparent differences.

Large percentage flow reversals were evident at parallel and impinging angles up to 40^0 as indicated in Fig.8. However, there were tests at near parallel directions which contained very low flow reversal conditions which was not generally expected.

This project has thus provided some quantitative data on the dynamic aspects of natural ventilation and the errors in the steady state prediction model have been shown to be significant. However not all the recorded data has been analysed and it has not been possible to extend the test program to consider the whole house, as was originally intended. The investigation would also be enhanced by the wind tunnel testing of a model of the house so that the wind pressures so derived could be compared with the recorded pressure data.

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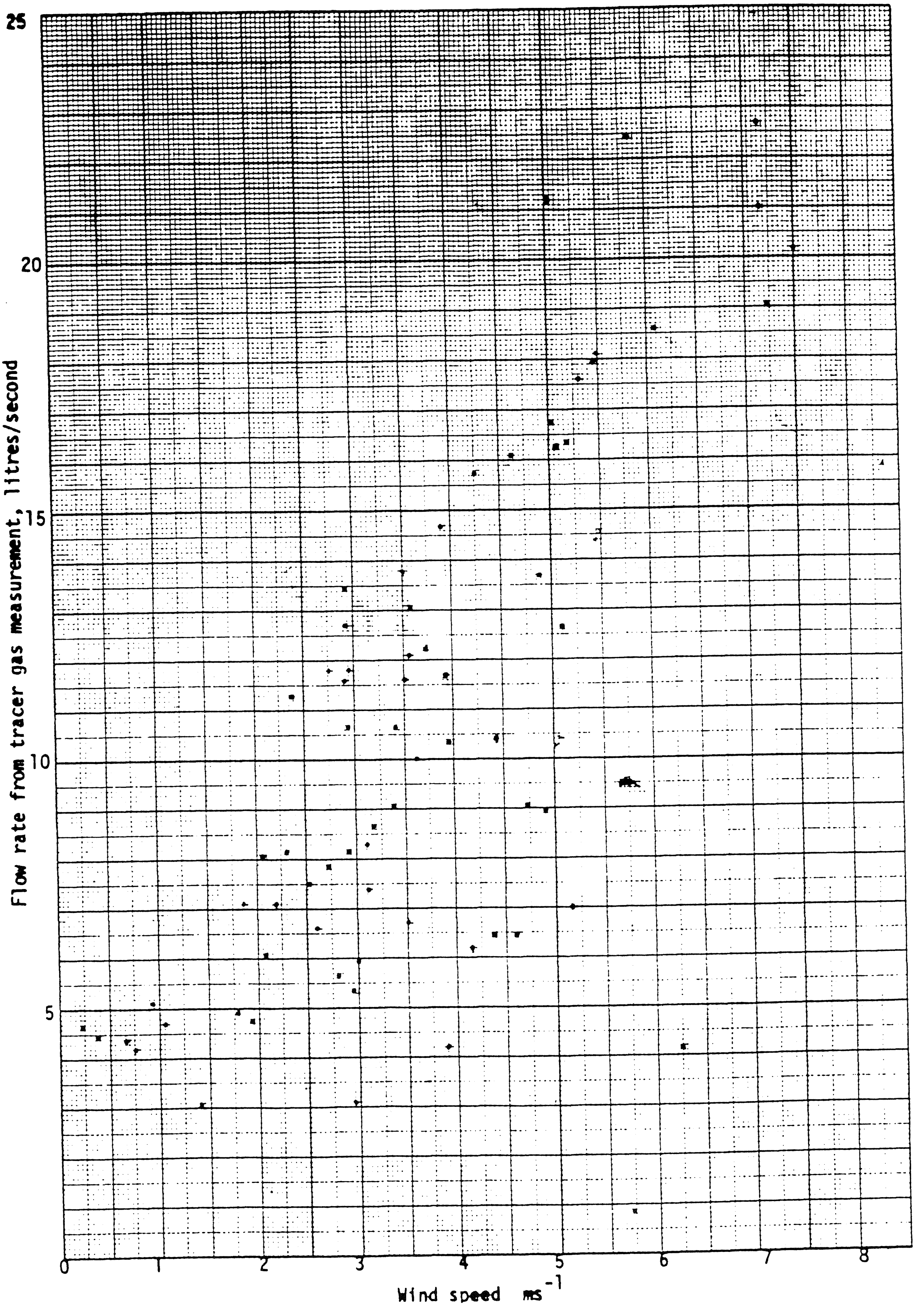

Fig. 1 Tracer gas flow rate vs wind speed

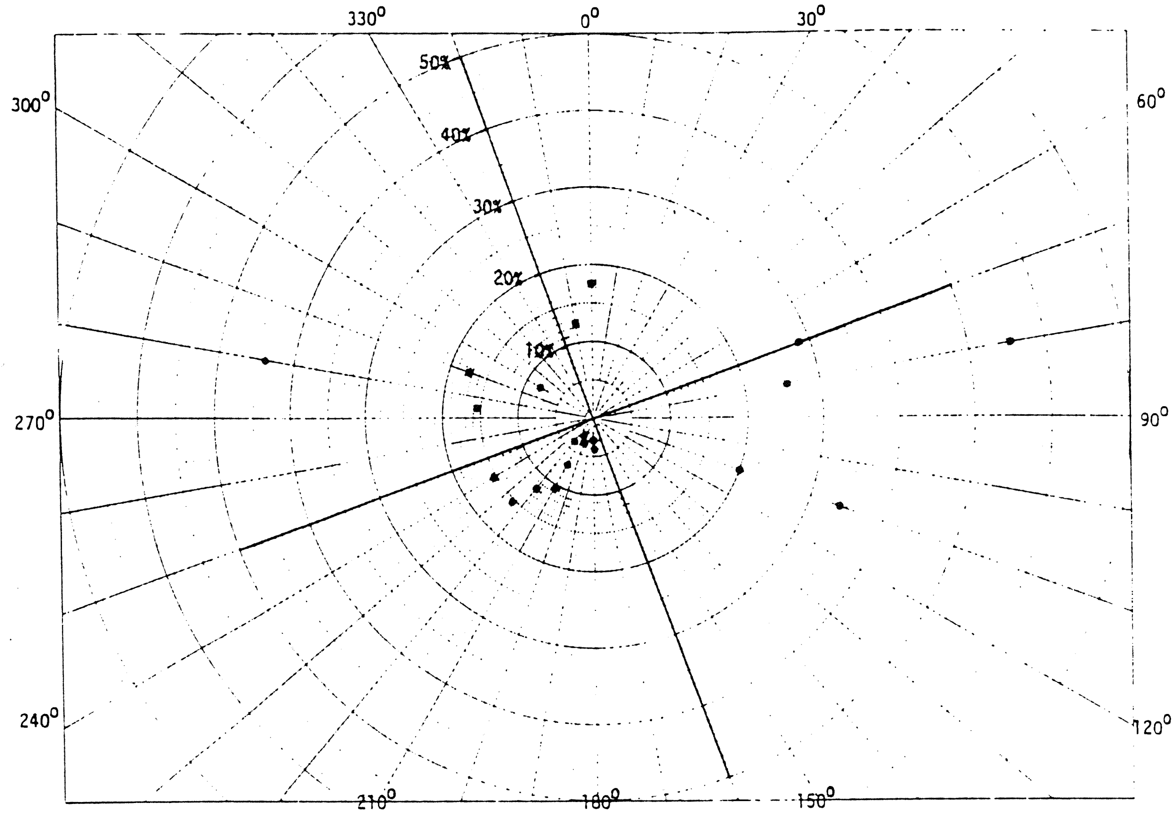

Fig. 4 Percent error between dynamic determination and tracer gas flow rate vs wind direction

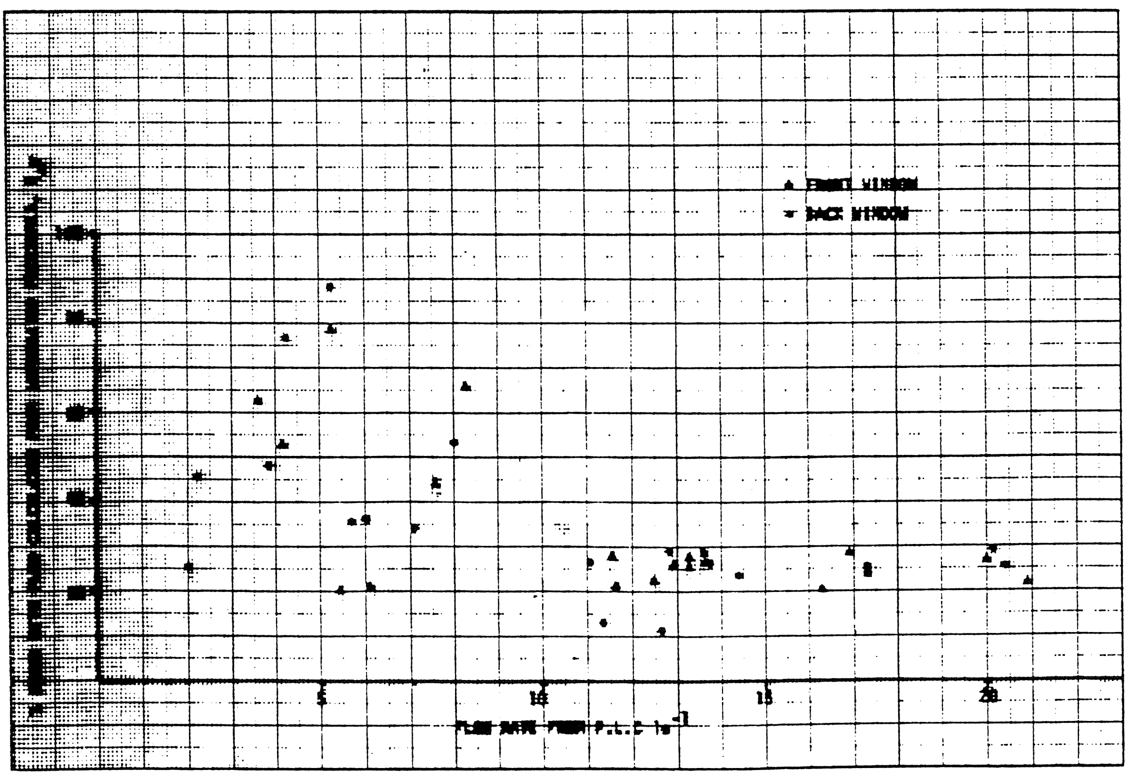

Fig. 5 Comparison of flow rates calculated from intergrated pressures with P.L.C. flow rates

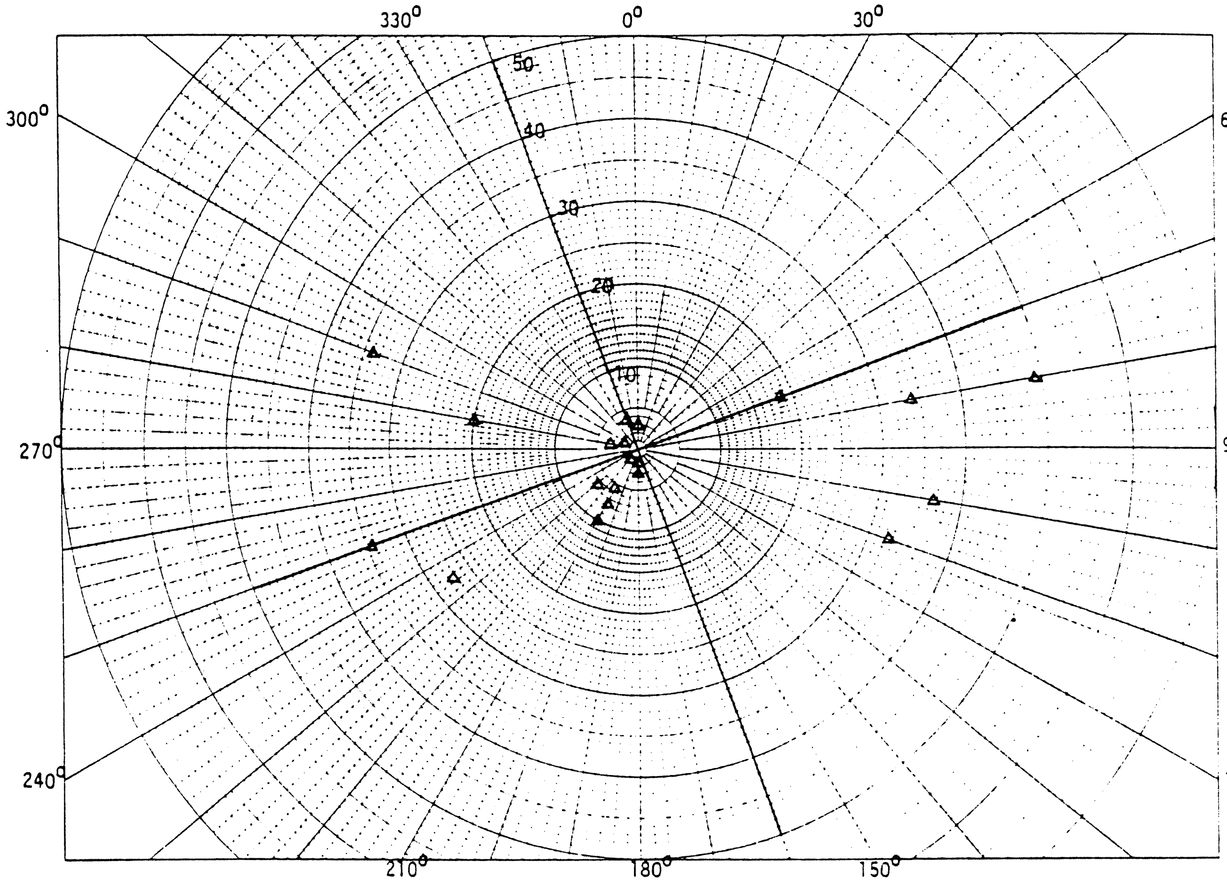

Fig. 8 Percent flow reversal vs wind direction