ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING ACCEPTABLE INDOOR AIR QUALITY

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VENTILATION PATTERNS OF WINDOWS AND ADJUSTABLE NATURAL VENTILATION SYSTEMS

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ABSTRACT

Measurements in a test room of 28.4 m^3 located at the top of a 3-story building have been made to determine ventilation rates of different natural ventilation systems. The systems under consideration were windows which are typical for residential buildings in Germany and various adjustable natural ventilation systems for installation in walls or window frames. The measurements take into account parameters as inside/outside temperature differences, wind velocity and direction, opening position and location of the different systems. The results are interpreted with respect to these parameters.

List of Symbols

A_o	equivalent opening area
C_o	initial concentration of tracer gas
c_t	concentration of tracer gas at time t
d	opening width of pivoted window
f_∇	geometric correction coefficient
g	gravitational constant
k	opening width of balance sash window
K	Kelvin
n	air-change rate
p	pressure
P	barometric air pressure
R	gas constant
t	time
Δt	temperature difference
T	absolute temperature
v	velocity of wind
V	volumetric air flow
V_{ab}	exhaust air flow
V_{zu}	supply air flow
V_l	air flow by infiltration (leakage rate)
V_{Ra}	volume of test room
α	coefficient for flow resistance
χ	factor for calculation of neutral flow axis
ρ_a	density of air, outside
ρ_i	density of air, inside

1. INTRODUCTION

The results presented in this paper have been taken from the work within the project "Natural Ventilation Systems" which is one of momentarily 14 ongoing projects of the research and development program "Ventilation in Residential Buildings". The program is sponsored by the Federal Ministry of Research and Technology (BMFT) of the Federal Republic of Germany. Detailed final reports to each of the projects will be published in German in the "Schriftenreihe Forschungsberichte des Bundesministers für Forschung und Technologie" -BMFT, Postfach 20 0706, D-5300 Bonn 2.

The project Natural Ventilation Systems has been elaborated in cooperation of Dornier System GmbH and Institut für Fenstertechnik, whereby measurements have been accomplished at the facilities of the Institut für Fenstertechnik.

The experience gained from these measurements can be taken to quantitatively judge upon the natural ventilation performance of systems which are common for residential buildings in Germany. The general validity of the results is restricted to some intent to the idealized conditions of a test room. Application of natural ventilation systems in buildings, however, will additionally be influenced by properties of the building and its surrounding. In addition, the behaviour of the inhabitants with respect to control and adjustment of windows and other naturally controlled systems will exert a decisive influence in the ventilation rates obtained in practical application with these systems.

2. PARAMETERS DETERMINING NATURAL VENTILATION

The magnitude of air flows and air-change rates in the test room under consideration which are due to natural ventilation depend basically upon the following three groups of parameters:

A. Driving forces

- temperature differences between inside and outside
- wind acting upon natural ventilation systems and air leakages in the building envelope

B. Natural ventilation systems

- size of opening
- geometry of opening
- internal air flow resistance of system
- position of opening, and location of different openings with respect to each other

C. Properties of test room

- air tightness/leakages with respect to magnitude and position
- positioning of heating elements
- room size, ground plan etc.

The experiments were conducted to give quantitative measures of temperature or wind induced ventilation on various types and positioning of natural ventilation systems.
The properties of the test room, however, were given as constant, apart from efforts trying to minimize the effects of air leakages.

3. DETAILS TO MEASUREMENTS

The test room is located on top of the roof of the "Institut für Fenstertechnik" in Rosenheim (Fig. 1). The test room had a volume of 28.4 m^3. East and west walls of the room were equipped with windows of the combination type balanced sash/pivoted window, which is a quite common window type in Germany. The same walls were equipped at certain periods with variable ventilation slots and adjustable natural ventilation systems. A door leading to the outside was installed at the east wall. The south wall was closed, whereas the north wall apart from a door leading to the interior of the building, had been equipped with a normally closed ventilation slot. This was done to be able to study stack effects due to the height of the adjacent building. Heating was performed by three electrical radiators located beneath the windows. For details see Figs. 2 and 3.

The measurements of the air-change rates applied the concentration decay method with methane (CH_4) as the tracer gas. Air-change (h^{-1}) and air-flow rates $\dot{V}$ (m^3/h) were determined by:

$$n = \frac{1}{t} \ln (c_o/c_t)$$

and $\dot{V} = n \cdot V_{Ra}$,

where c_o and c_t are the concentrations of the tracer gas at time o resp. t and V_{Ra} is the volume of the test room.

The following systems were tested:

- windows of the combination type balanced sash/pivoted at different opening positions, each window having a size of 1.1 m x 1.3 m.
- Ventilation slots having a length of 80 cm. Opening width and position in the test room have been varied
- Four different types of adjustable natural ventilation systems, as available on the German market. Some of them are constructed for noise dampening purposes (see Fig. 13).

The internal flow resistance of the adjustable ventilation systems was determined by using a test device which normally is applied for measurements of the tightness of window seals.

4. MEASUREMENT RESULTS

4.1 Air Infiltration characteristics of the test room

To quantify the air-leakage rate of the test room and its dependence from temperature and wind, several measurements have been conducted with windows and other ventilation systems tightly closed.
The results, plotted in Fig. 4, show that temperature and wind induced natural ventilation is not simply additive. If driving forces due to temperature differences and wind pressure prevail at the same time, then ventilation is mainly determined only by the force which is momentarily dominating. This effect had been stated already theoretically by P.R. Warren, 1976.

Warren, P.R.: Natural Infiltration Routes and their Magnitude in Houses - Part 1:
Preliminary Studies of Domestic Ventilation
Building Establishment, Garston 1976

The air-change rate due to leaks is generally of the order 0.1 to 0.3 h^{-1}. This may seem to be rather high but can be attributed to the small volume of the test room and to the considerable number of leakage sources from several windows, doors and flexible elements for installation of different systems. Nevertheless, by sealing most of the obvious leakage sources, it was tried to keep air leakage as low as possible.

4.2 Balanced sash/pivoted window

To give an idea of the magnitude of air flows caused by different magnitude of window-opening position, the range of all measurement data taken during 1981 have been plotted in Figs. 5 and 6 regardless what outside weather conditions were prevailing. For opening widths k or d of 6 to 12 cm we can expect air flows from appr. 50 to 250 m^3/h. Considering an average sized room of 5 x 4 m^2 floor area having a volume content of 50 m^3 then this would give rise to air-change rates of 1 to 5 h^{-1}, if continous ventilation is applied with this type of window. As nowadays we do not consider continuous ventilation rates of more than 0.5 to 1 h^{-1} to be energy efficient, ventilation by windows with an opening width of 6 to 12 cm should only be applied temporary such as e.g. 5, 10 or 15 minutes per hour. In Germany, however, continous ventilation of certain rooms (e.g. sleeping room during daytime) by a balanced sash of appr. 12 cm opening width is still rather common.
An opening width of 1 to 3 cm seems at first sight more likely to be suited for continous ventilation, but dependence of air flows on temperature and wind still demand an energy-concious behaviour of inhabitants, if excessive energy losses above the necessary limit shall be avoided. The detailed influences of temperature, wind, opening width and positioning of windows will be shown in the following.

To show the temperature dependence of the air flow all measurement data of figs. 7, 8 and 9 have been taken at wind speeds well below 1.5 m/s. As the air flow increases linearily with opening width k resp. d, if these are in the range 0 to 12 cm, the air-flow rates of fig. 9 have been normalized by division through k resp. d.
Details to the theoretically calculated value of the temperature induced air-flow rates are given in the appendix.

The influence of velocity and direction of wind has been studied at inside/outside temperature differences appr. 0 k (Figs. 10, 11 and 12).
Fig. 10 shows a linear dependence of the air change with respect to wind velocity, if wind direction is constant. At the same wind velocity but at different directions of wind there can be considerable differences. The air flow is larger by a factor of appr. 2 between parallel flow direction with respect to window and perpendicular flow to the windward positioned window.
The air flow increases linearly with opening width in the measured range of k = 1 to 6 cm, see Fig. 11.

Fig. 12 shows the effects of cross ventilation with two windows on opposite walls compared to two resp. one window at the same side of the test room. Whereas opening of two windows roughly doubles ventilation caused by one single window, cross ventilation causes ventilation rates to go up by a factor of 8 to 10. In practical circumstances wind induced cross ventilation will not be applied, apart from eventually removing heat loads in summer-time. But we should keep in that cross ventilation effects can cause excessive airchanges, if e.g. one window has been opened at one side of a building and considerable air leakages exist at the opposite side.

4.3 Ventilation slots and adjustable natural ventilation systems

The manually adjustable natural ventilation systems under consideration are common-type systems available on the German market. Mainly they are applied if excessive outside noise levels prohibit opening of sound-proof windows. Fig. 13 gives some data to the construction of these systems. The systems available on the German market are not equipped with any self-regulating devices for the control of air flows such as e.g. automatic variation of air-inlet area with respect to outside temperature or inside/outside pressure difference. Adjustment is purely manual depending upon the individual judgement of inhabitants.

The measurements from the test-bench showed that the efficiency of these adjustable systems can be sufficiently well described by using an equivalent opening area of a ventilation slot. From this reason most experiments were conducted for ventilation slots having a length of 700 mm each and a width of 10 to 20 mm.

Temperature induced ventilation is shown in Fig. 14 and 15 for different positioning of the slots. One horizontal slot exhibits almost no dependence with increase in temperature difference. The increased level of ventilation compared to the leakage rate seems rather to be due to wind effects still present below 1.5 m/s. Two horizontal slots at different height and one vertical slot show a similar temperature behaviour as found for opening of windows.
The dependence on wind velocity for different positions and numbers of slots is given in fig. 16. If all slots are positioned at one side of the room, virtually no difference in the ventilation rates can be seen when the total opening area of each slot arrangement is the same (104 cm^2 for the data of fig. 16). Cross ventilation by slots at opposite sides of the room, yields higher ventilation rates even with the total opening area being the same.

APPENDIX

Calculation of temperature induced air-flow rates

For the calculation the following basic three relationships are used:

Pressure difference of air at different temperatures

(1) $\Delta p = (\rho_{t_2} - \rho_{t_1}) \cdot g \cdot z$

where ρ_{t_i} = density at temperature t_i

g = gravitational constant

z = altitude

Air velocity v due to pressure difference

$$v = (2 \cdot \Delta p/\rho)^{1/2}$$

or by inserting equ. (1)

(2) $v(z) = 930 \cdot \alpha \cdot z^{1/2} \cdot \Delta t^{1/2}$

where α is a factor for the air flow resistance at an opening

Equation of continuity

(3) $\dot{V}_{zv} = \dot{V}_{ab}$

where $\dot{V}_{zu}$ and $\dot{V}_{ab}$ are the air flows to and from a room.

For a rectangular opening (see fig. 17) of dimension BxH we thus get:

$$\dot{V} = \int_0^{\chi H} v(z)\, B\, dz$$

where $\chi \cdot H$ denotes the height of the natural axis.

With $\chi \cdot H = H/2$ and $v(z)$ from equ. (2) this becomes:

$$\dot{V}_{\square} = 220 \cdot \alpha \cdot B \cdot H^{3/2} \cdot \Delta t^{1/2}$$

For the pivoted window (fig. 18) of opening width d we have air flow through a rectangular and triangular shaped area. The total air flow $\dot{V}_d$ is thus given by:

$$\dot{V}_d = \dot{V}_{\square} + \dot{V}_{\Delta}$$

$$\dot{V}_d = (220 \cdot H + 329 \cdot f_{\nabla} \cdot B) \cdot \alpha \cdot d \, (\Delta t \cdot H)^{1/2}$$

where f_{∇} is a geometric correction coefficient for the deviation from an idealized triangular shape.

For the pivoted window - as used in the measurements - of dimensions B = 1.0 m, H = 1.2 m and f_{∇} being 0.7 this yields

$$\dot{V}_{d \,.\, Test} = 540 \cdot \alpha \cdot d \cdot \Delta t^{1/2}$$

The neutral axis of height $\chi \cdot H$ for the balanced sash (fig. 19) has to be calculated from equ. (3). We get the relation:

$$\frac{B}{H \cdot f_{\nabla}} = \frac{4}{15} \left[\frac{2\chi^{5/2}}{(1-\chi)^{1/2}} + 2\chi^2 + \chi - 3 \right]$$

The air flow $\dot{V}_K$ for the balanced sash thus becomes

$$\dot{V}_K = 496 \cdot \chi^{5/2} \cdot \alpha \cdot f_{\nabla} \cdot k \cdot H^{3/2} \cdot (\Delta t)^{1/2}$$

The relative height χ of the neutral axis and the ventilation factor $\chi^{5/2} \cdot f_{\nabla}$ is sketched in fig. 20.
For the tested balanced sash with B = 1.0 m, H = 1.2 m and f_{∇} = 0.7 the relative height χ equals 0.90.
The air flow for the test window is thus given by:

$$\dot{V}_K = 350 \cdot \alpha \cdot K \cdot \Delta t^{1/2}$$

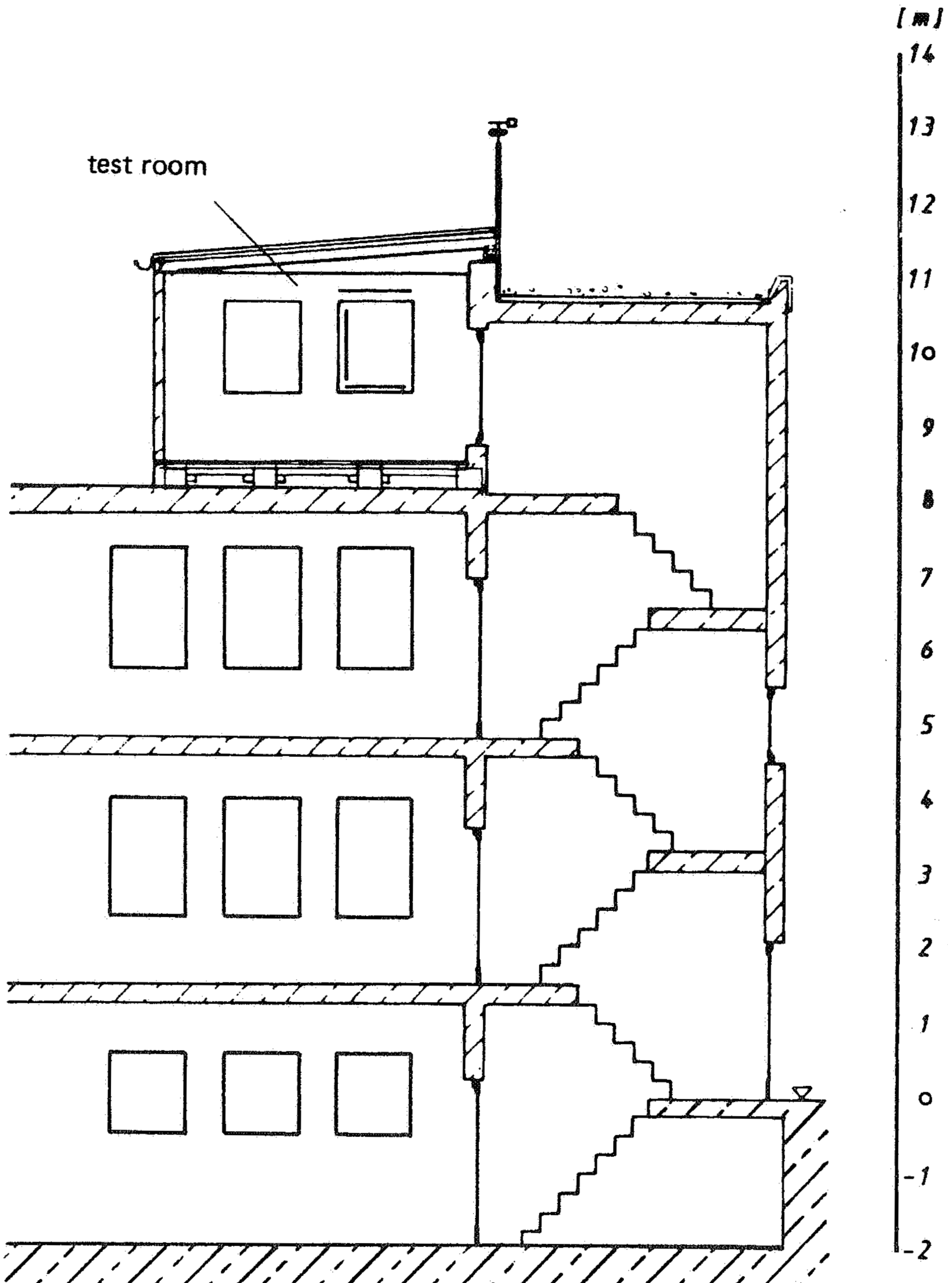
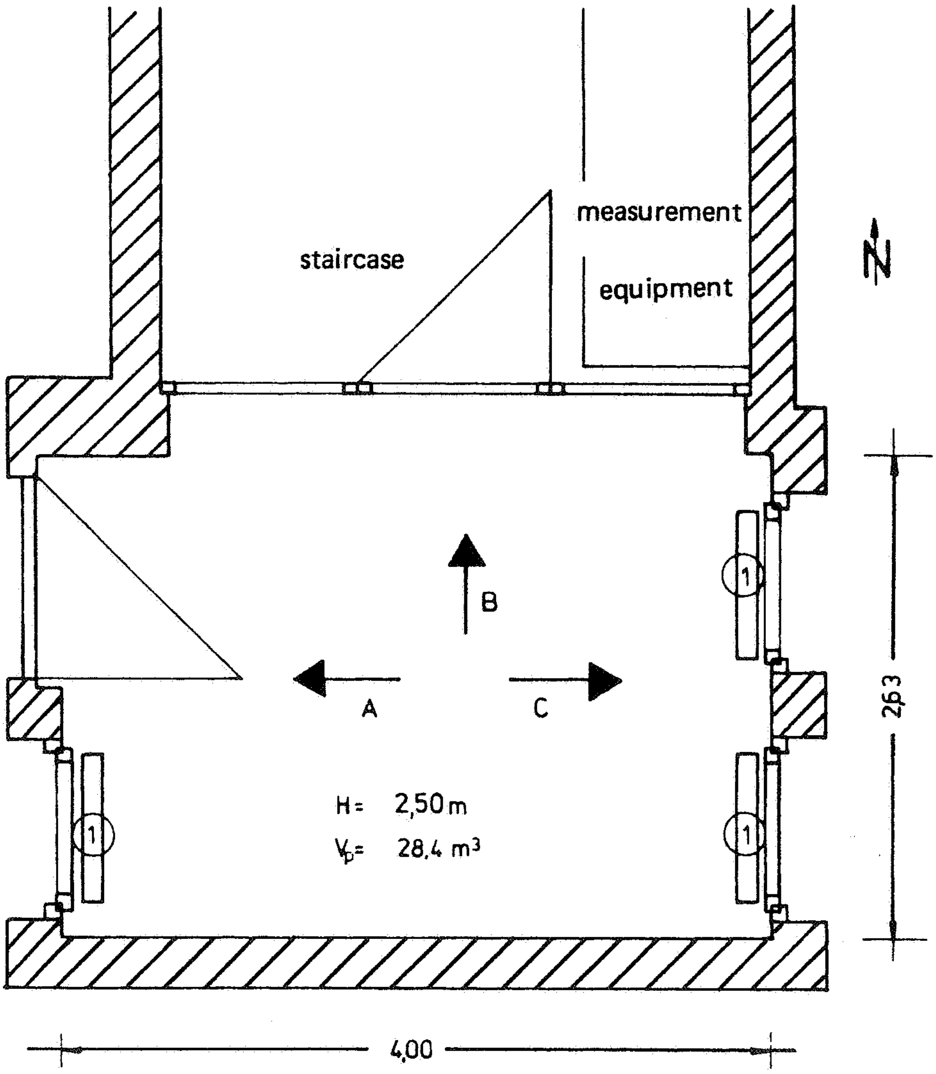
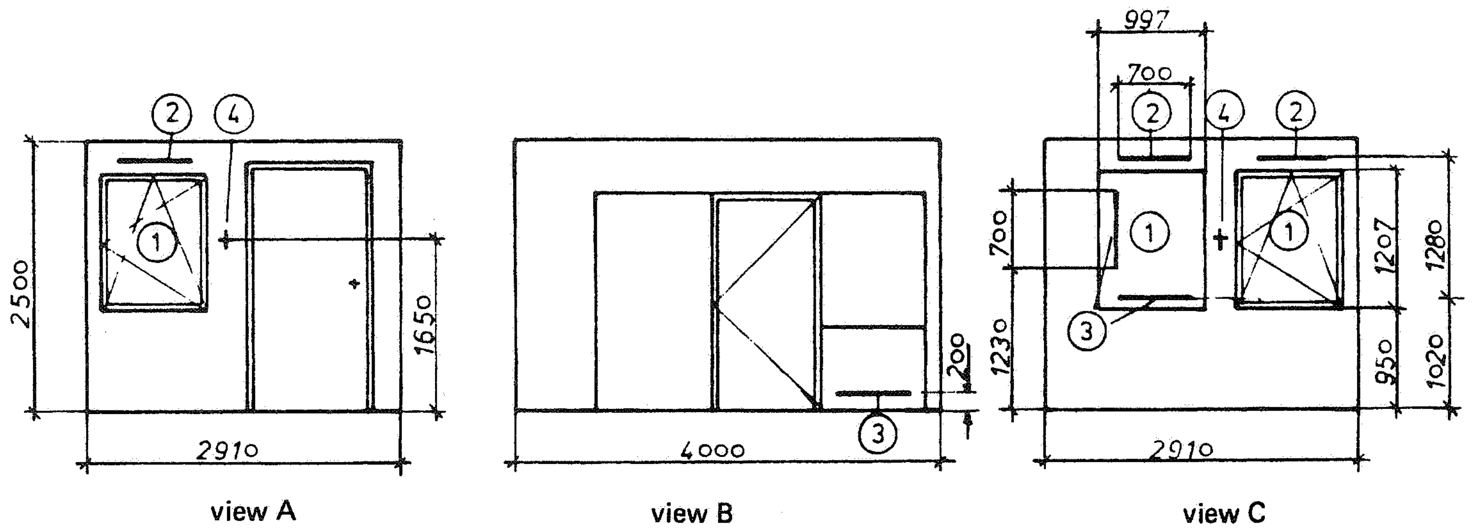


Fig. 1 : Sketch of institute building showing position of test room (view from east)



(1) electrical radiators 1000 W

Fig. 2 : Ground plan of test room
A, B, C indicates views of fig. 3



1 — test windows

2 — installation of different adjustable ventilation units or ventilation slots

3 — installation of ventilation slots

4 — measurement of external pressure

Fig. 3 : **Test room – views of west (A), north (B) and east wall (C)**

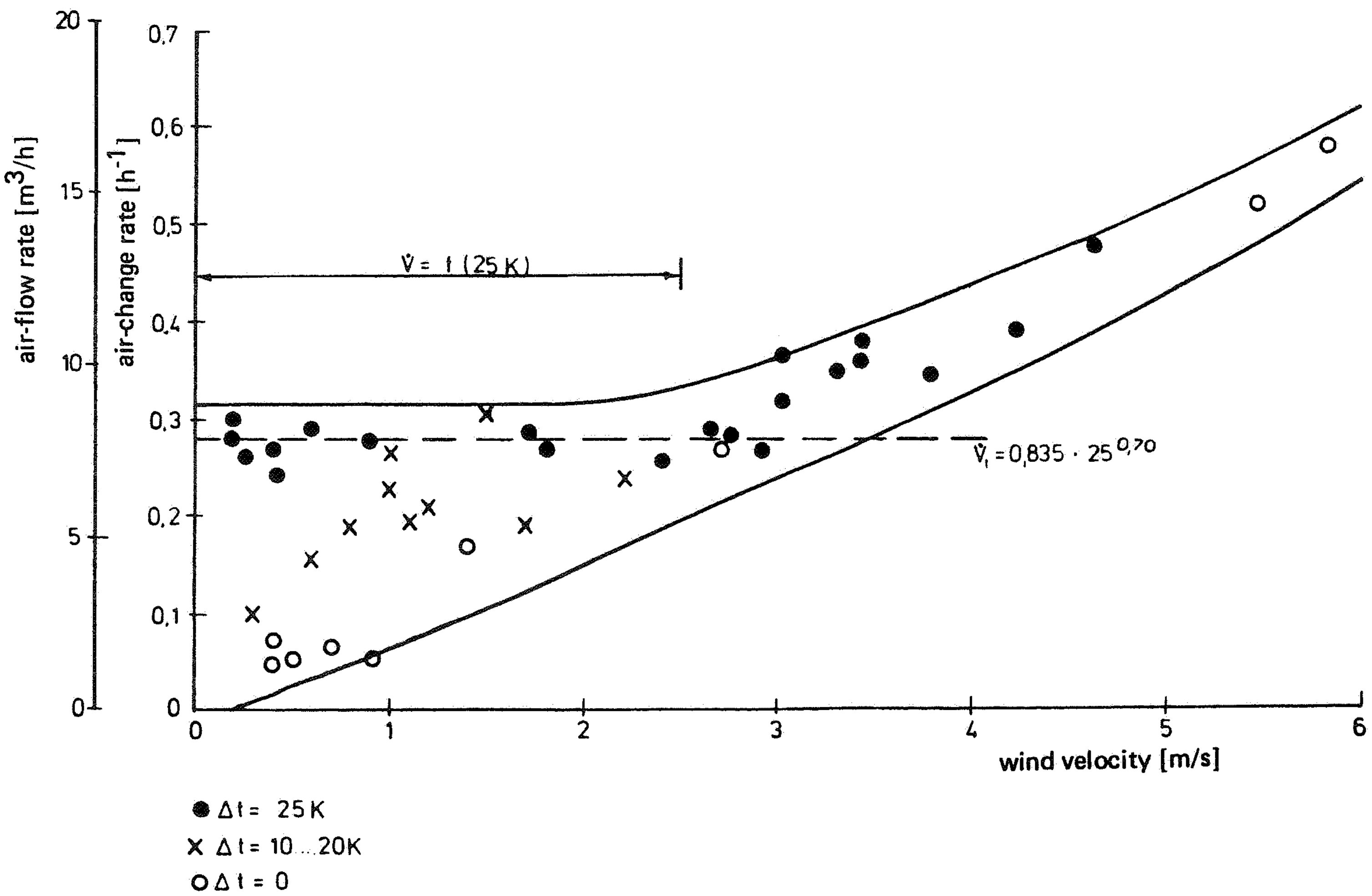


Fig. 4 : **Air infiltration rate through leakages. Dependence on wind velocity at various inside/outside temperature differences**

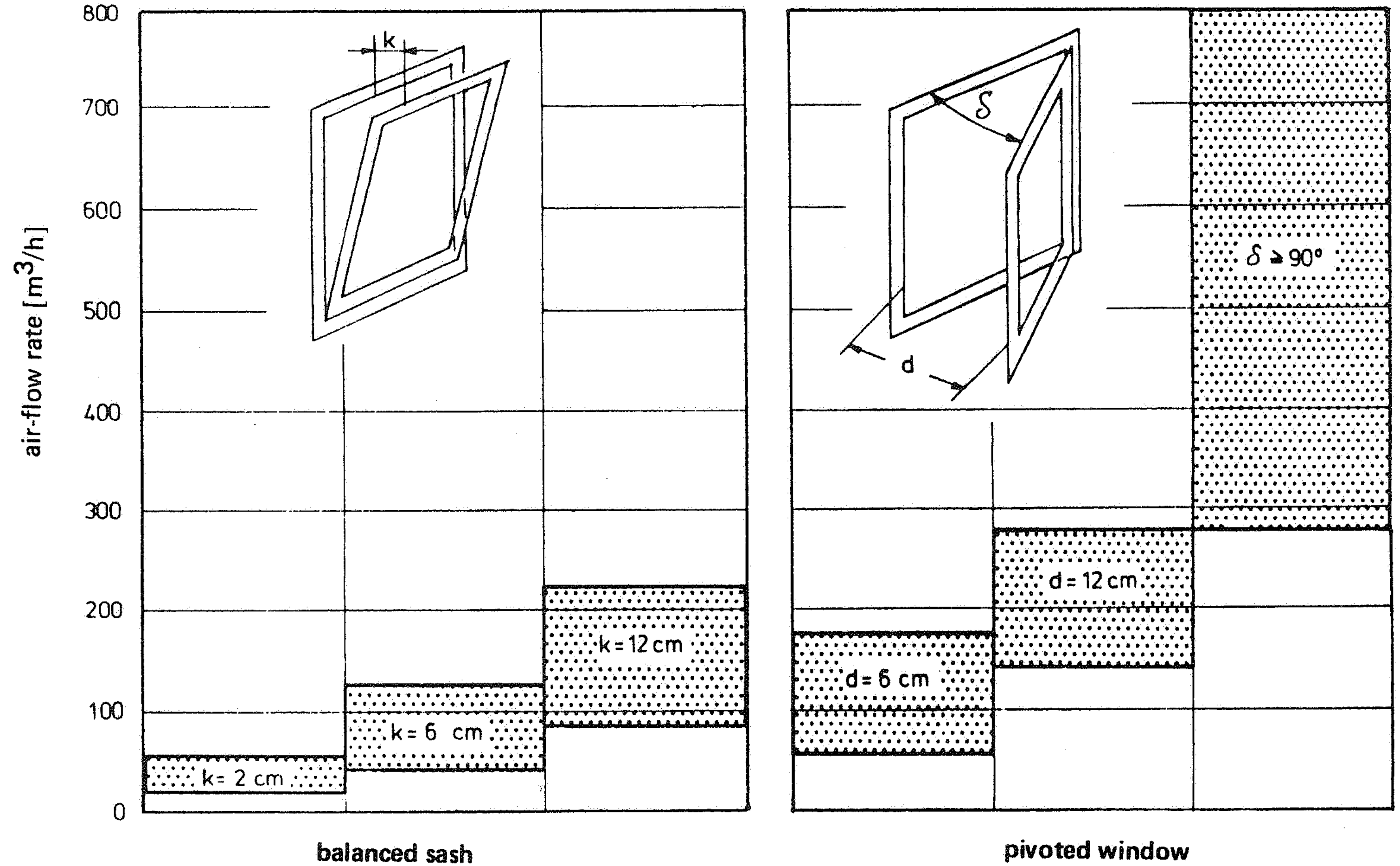


Fig. 5 : Range of all measurement data taken during 1981 for different opening widths of balanced sash and pivoted window.
Wind velocities: 0 to 6 m/s
Inside/outside temperature difference: 0 to 25 K

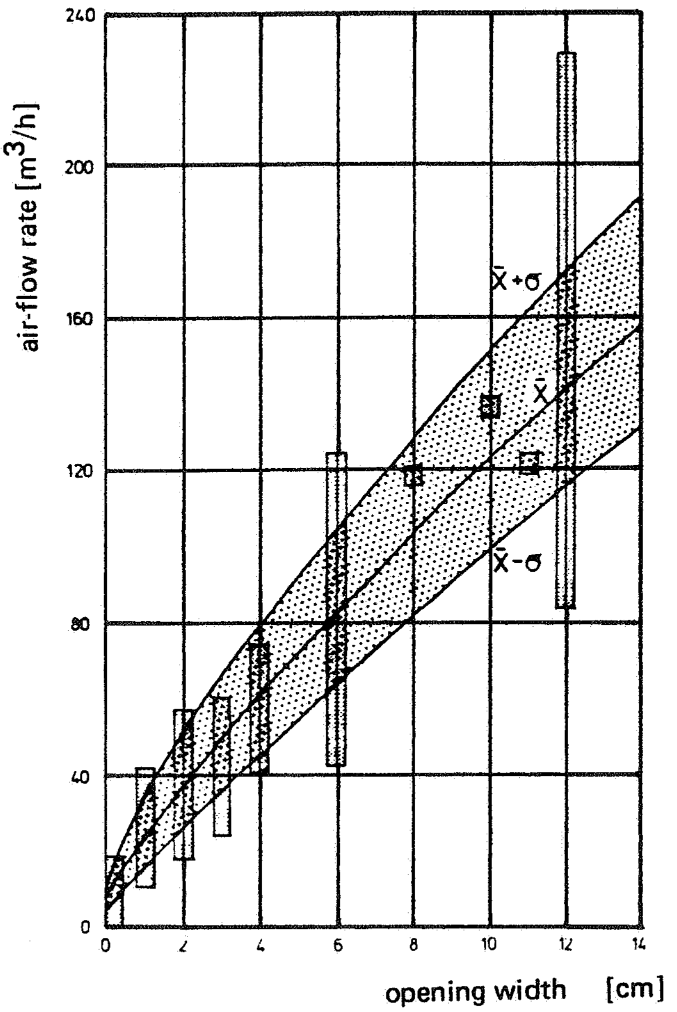


Fig. 6 : Balanced sash window — air-flow rates at different opening widths.
Wind velocities: 0 to 6 m/s
Inside/outside temperature difference: 0 to 25 K

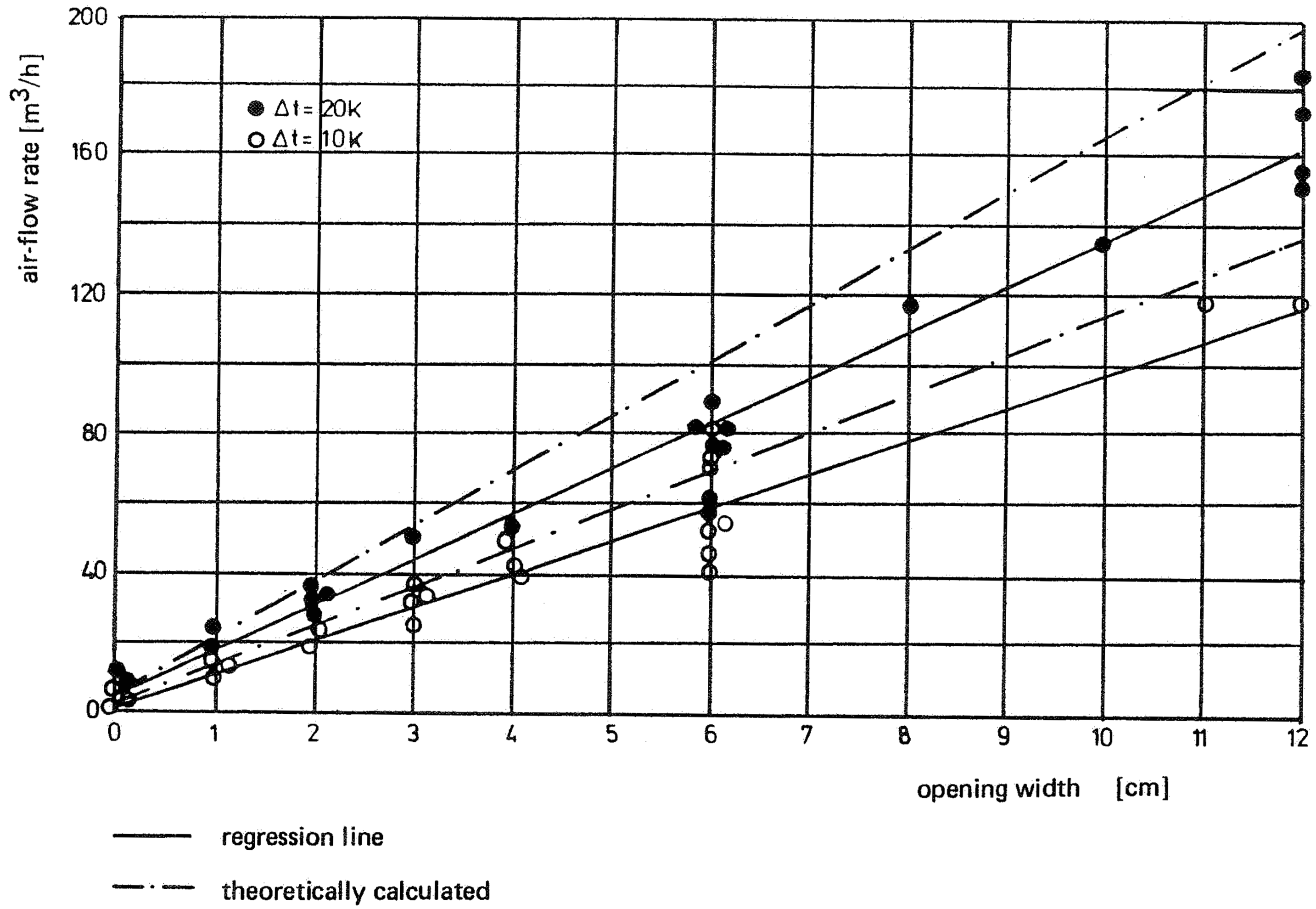


Fig. 7 : **Temperature induced ventilation of balanced sash.**
Dependence on opening width.
Wind velocity below 1.5 m/s

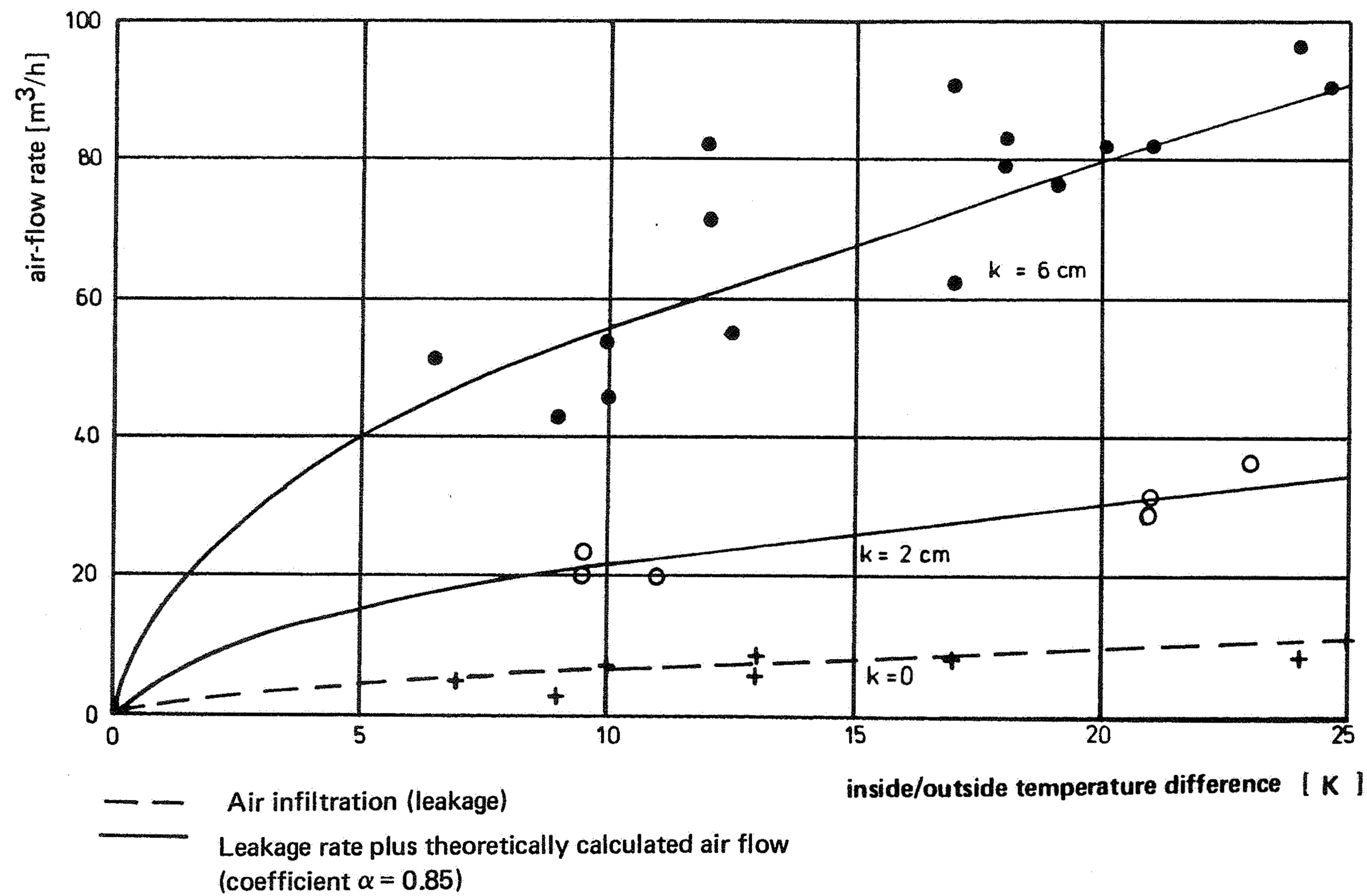


Fig. 8 : **Temperature induced ventilation of balanced sash.**
Dependence on inside/outside temperature difference.
Wind velocity below 1.5 m/s

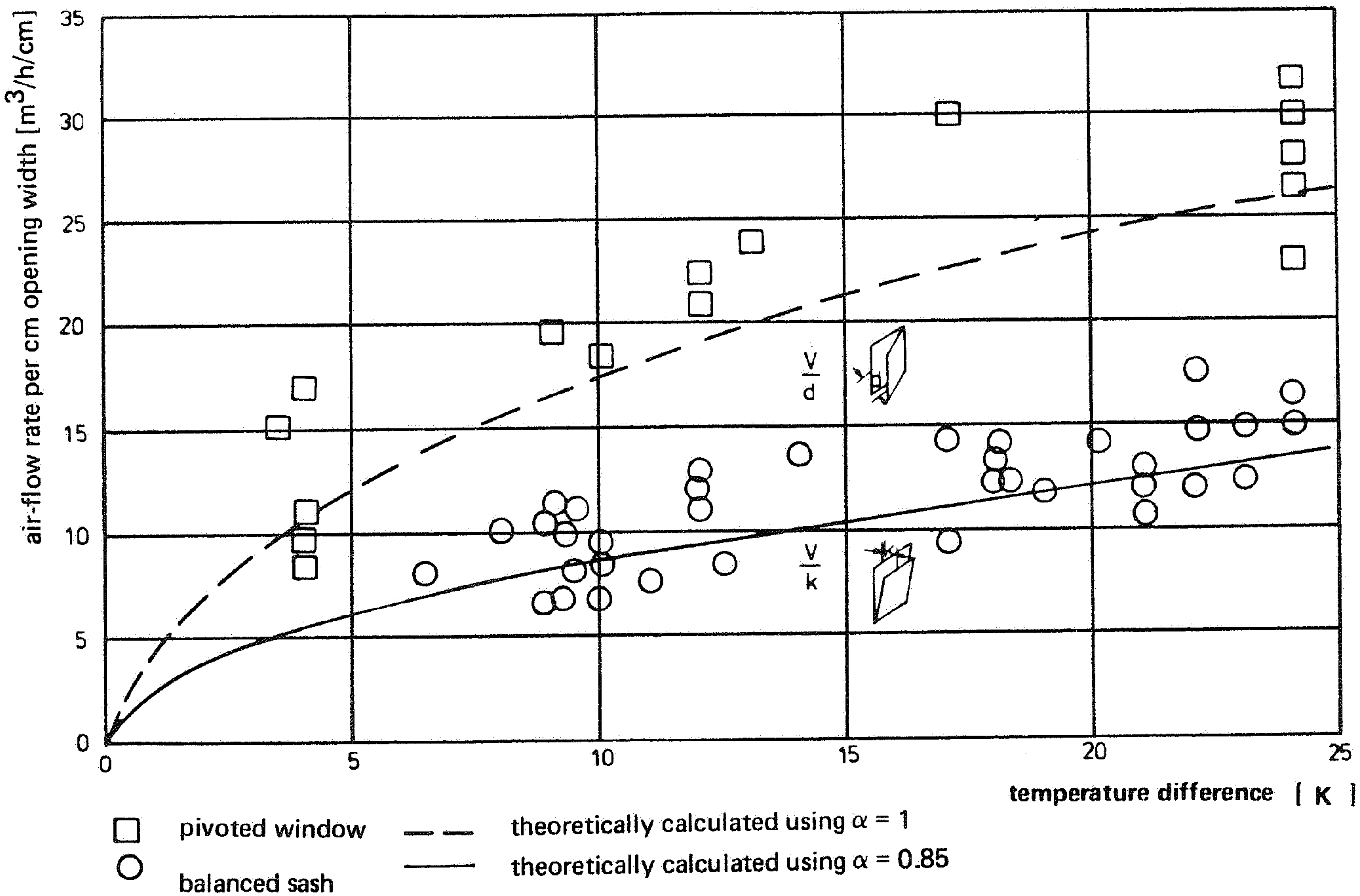


Fig. 9 : **Temperature induced ventilation of balanced sash / pivoted window. Dependence on inside/outside temperature difference of air-flow per cm of opening width d resp. k. Wind velocity below 1.5 m/s**

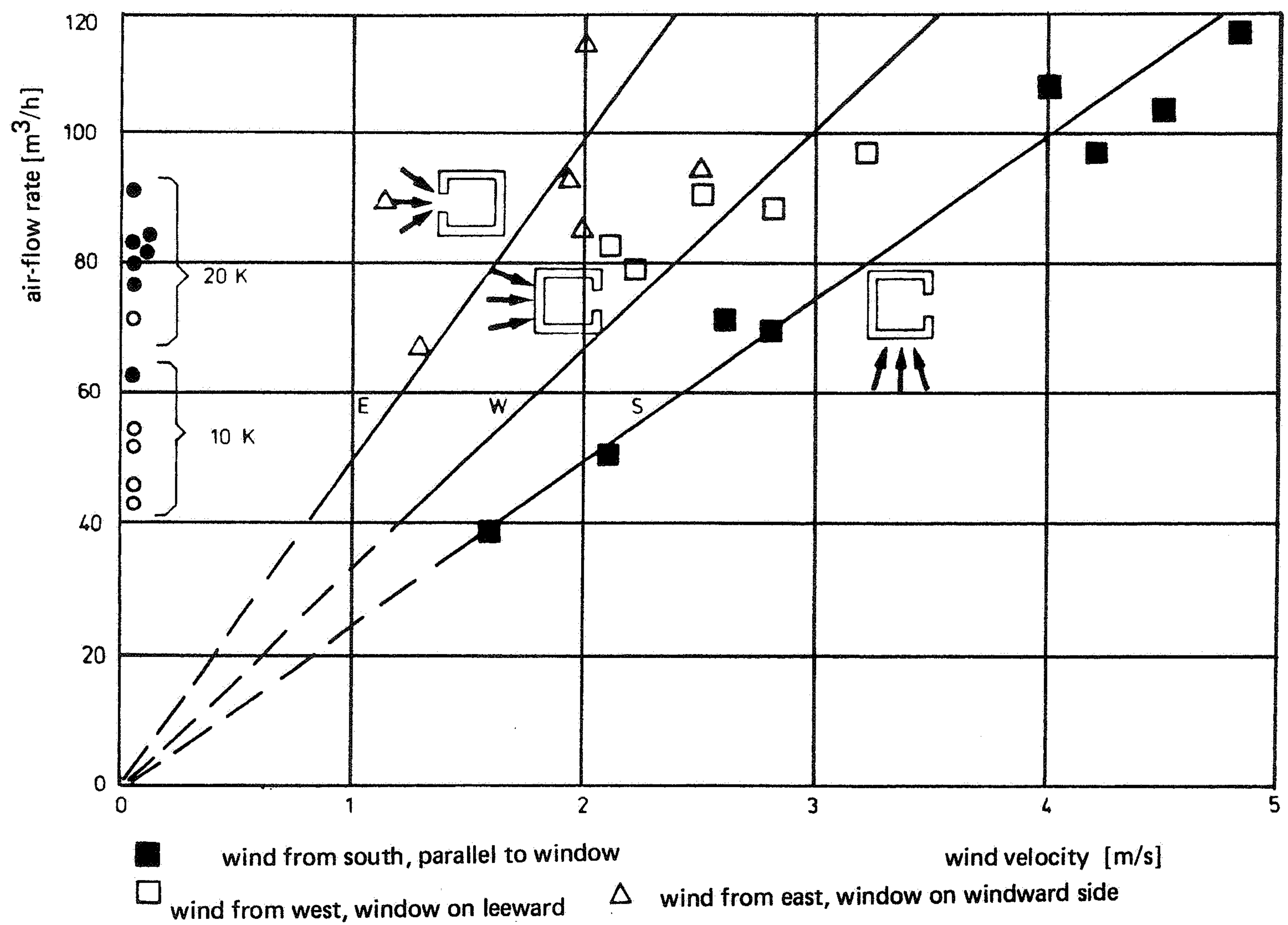


Fig. 10 : **Wind induced ventilation of balanced sash.**
Dependence on wind velocity and wind direction.
Opening width k = 6 cm, temperature difference appr. 0 K
For comparison temperature induced ventilation (at wind velocity appr. 0 m/s) is given for Δt = 10 resp. 20 K

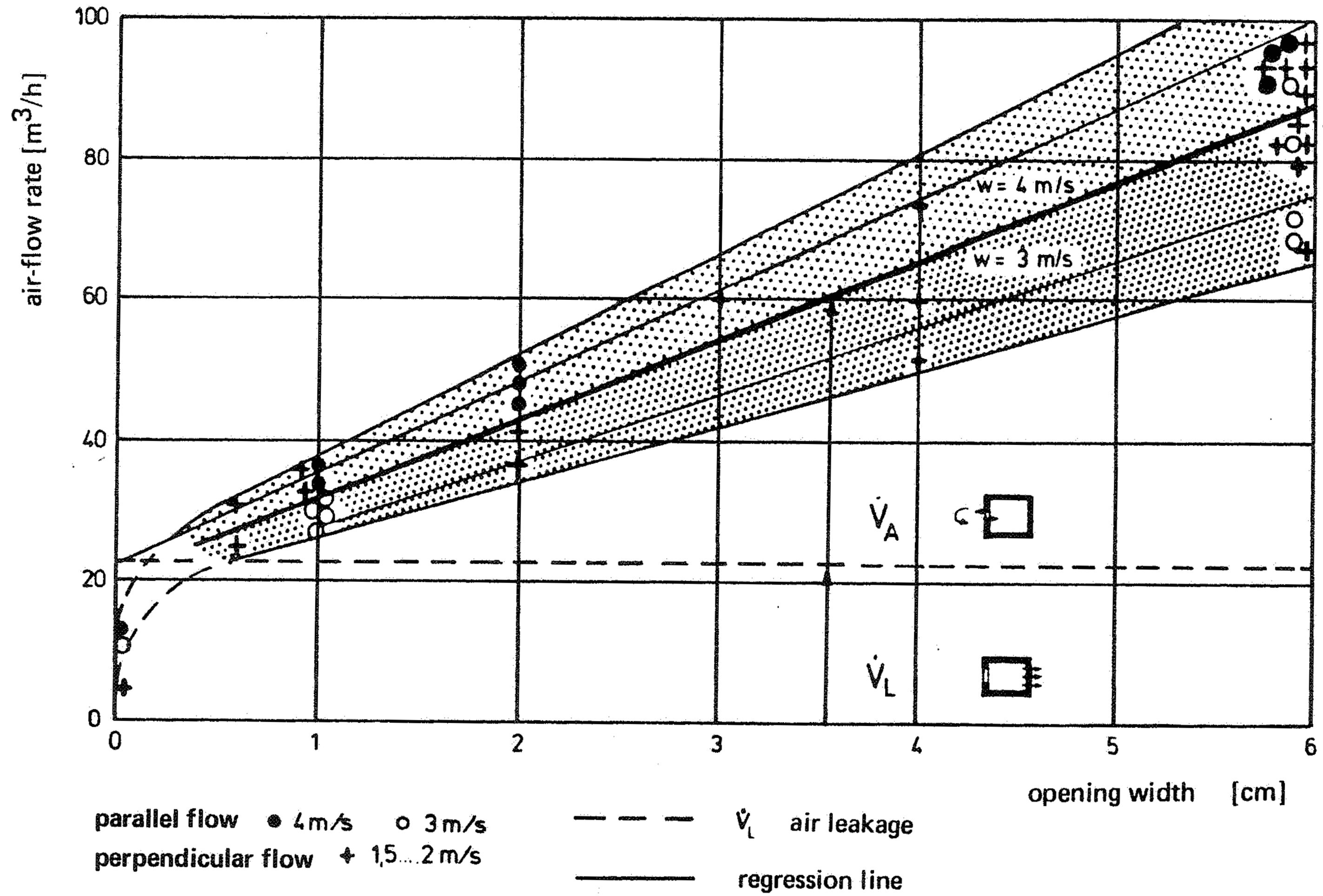
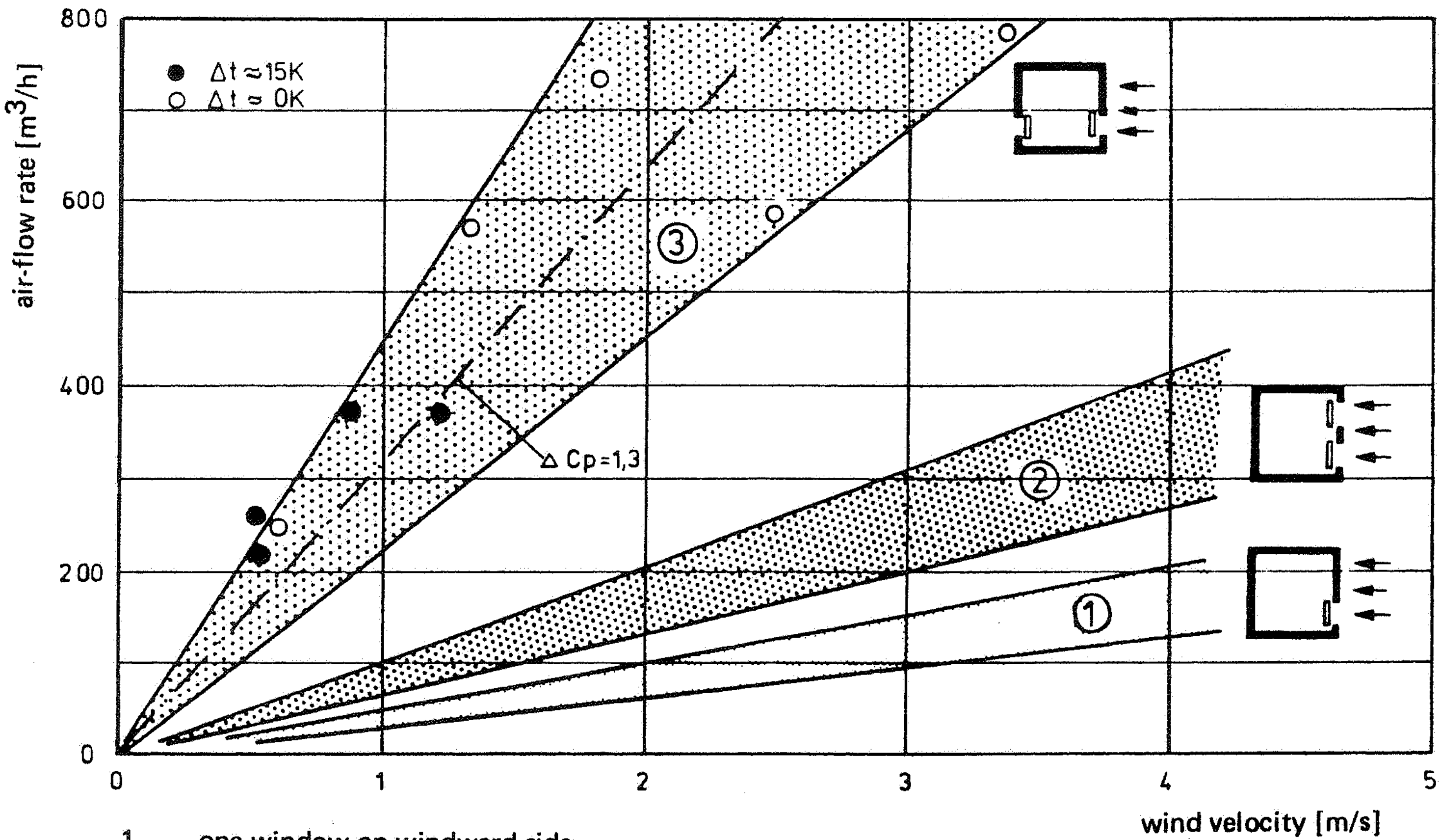


Fig. 11 : **Wind induced ventilation of balanced sash.**
Dependence on opening width at constant wind velocity.
Temperature difference Δt appr. 0 K



1 — one window on windward side

2 — two windows on windward side

3 — cross-ventilation, one window each at windward and leeward side

Fig. 12: Wind induced cross-ventilation by two balanced sash windows at opposite sides of the test room.
For comparison data for windows installed at one side are given.
Opening width k = 6 cm in each case

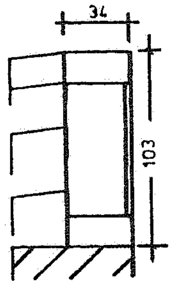
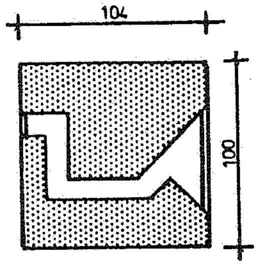
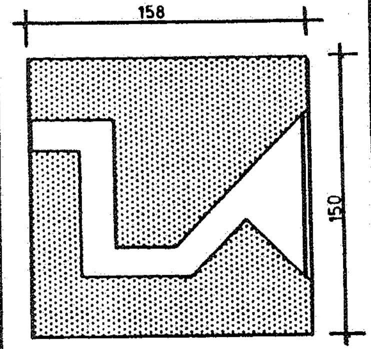
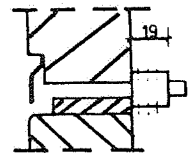
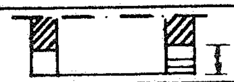
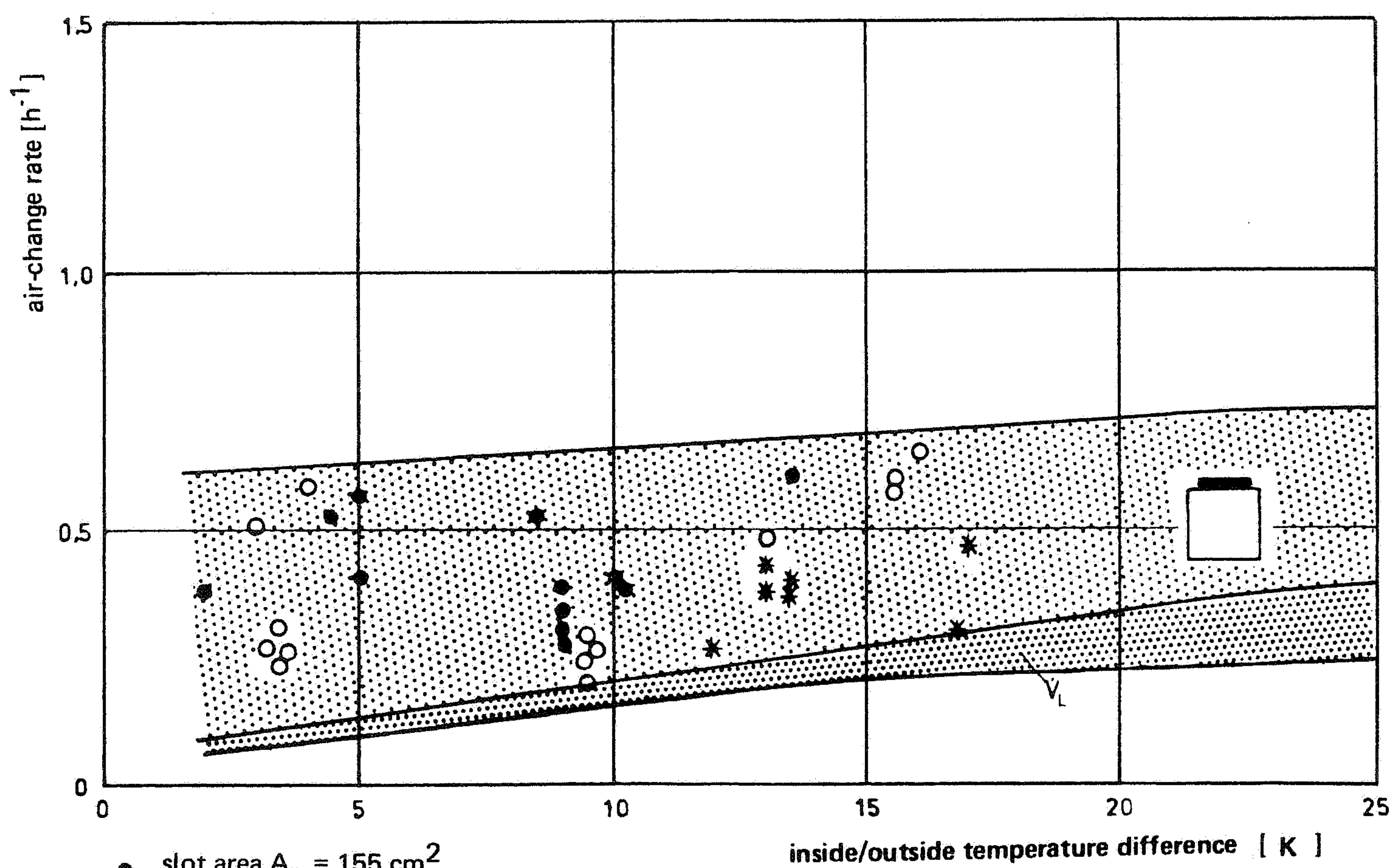
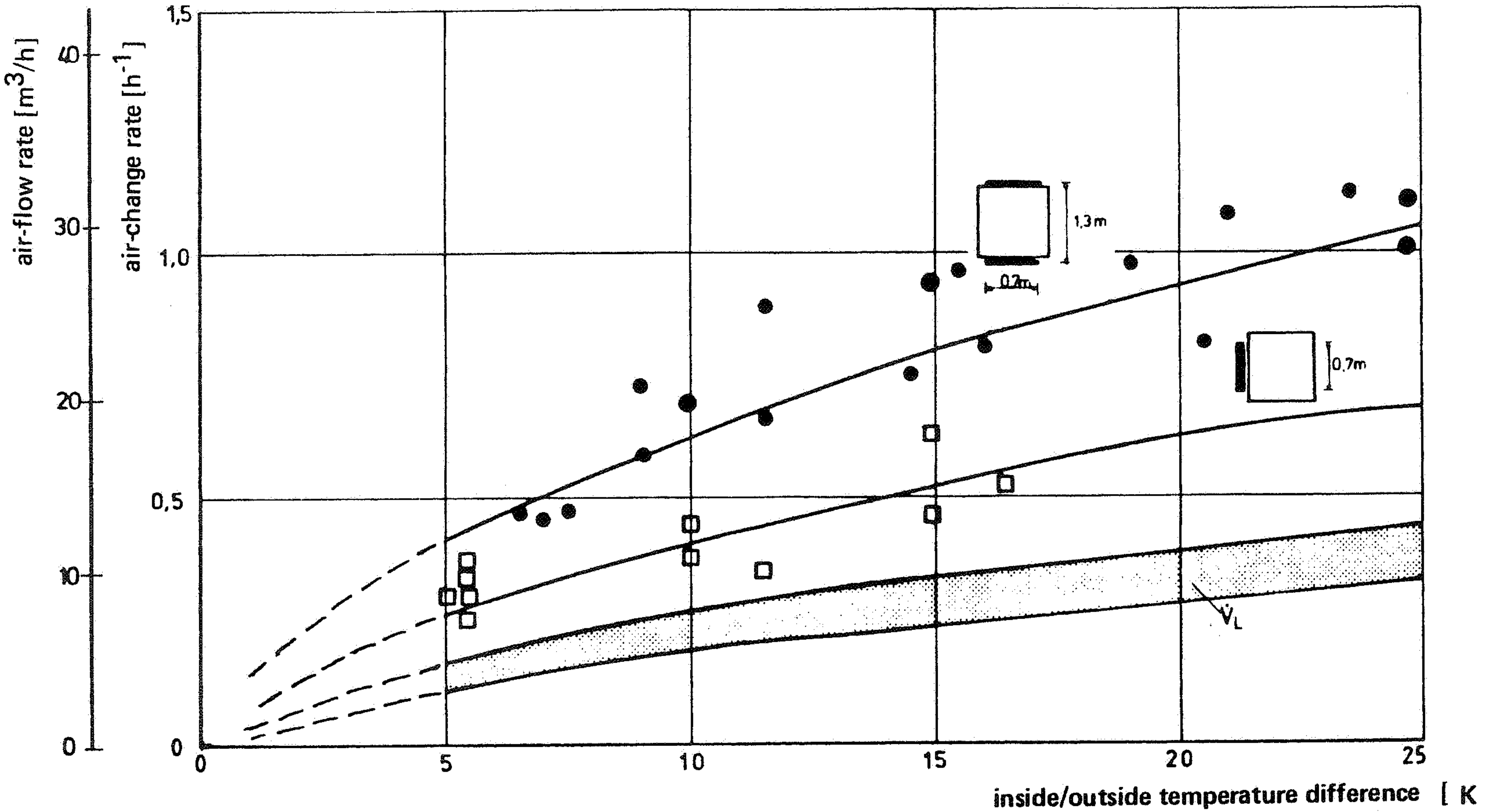
vertical cut of investigated systems	 	 	 	
test number	1	2	3	4
cross sectional scheme				
open flow area [cm^2]: outside	95	60	73	52
centre	580	79	115	52
inside	111	107	107	40

Fig. 13: **Sketch of adjustable natural ventilation systems**



- ● slot area $A_o = 155\ cm^2$
- ○ slot area $A_o = 104\ cm^2$
- ✱ adjustable ventilation system $A_o = 23$ to $53\ cm^2$
- $\dot{V}_L$ air leakage

Fig. 14 : **One horizontally installed adjustable ventilation system or single slot of different area.**
Dependence on temperature dependence at low wind speed (below 1.5 m/s)



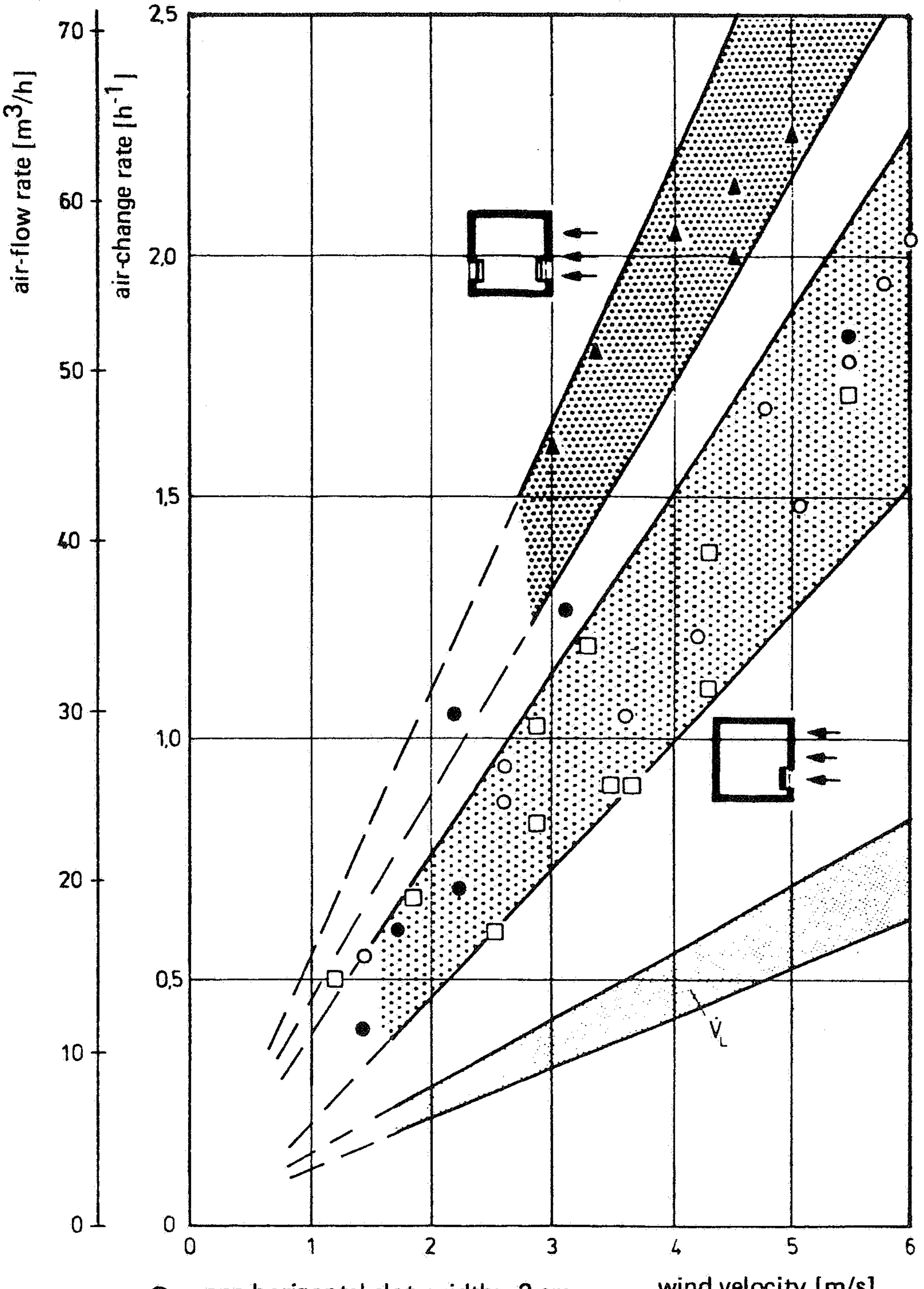
● Two horizontal openings at different height, each $A_o = 52\ cm^2$

□ One vertical slot of $A_o = 104\ cm^2$

$\dot{V}_L$ air leakage

—— theoretically calculated + air leakage

Fig. 15 : **Temperature induced ventilation of adjustable ventilation system. Wind velocity below 1.5 m/s**



○ one horizontal slot, width: 2 cm

● one vertical slot, width: 2 cm

□ two horizontal slots at different height at one side, width of each: 1 cm

△ two horizontal slots at opposite sides, width of each: 1 cm

Fig. 16 : Influence of wind velocity of 4 different arrangements of ventilation slots. Each arrangement has the same total opening area

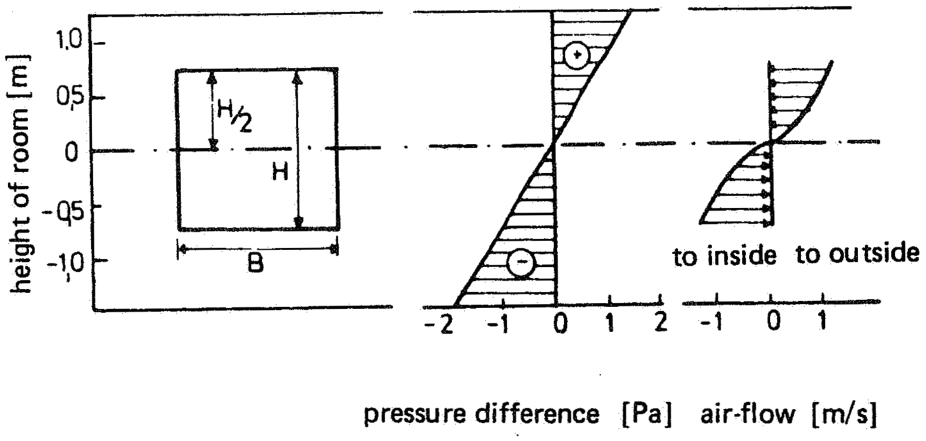


Fig. 17 : **Pressure and flow distribution at rectangular opening**

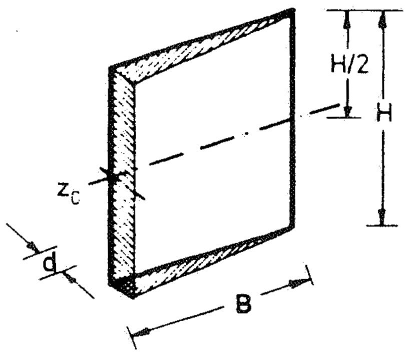


Fig. 18 : **Geometric parameters of pivoted window**

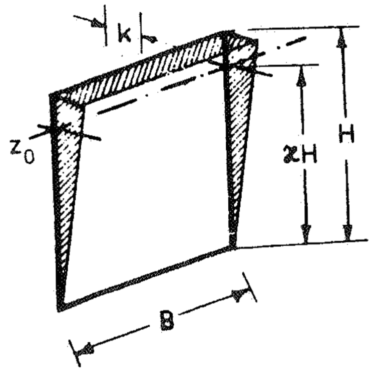


Fig. 19 : **Geometric parameters of balanced sash**

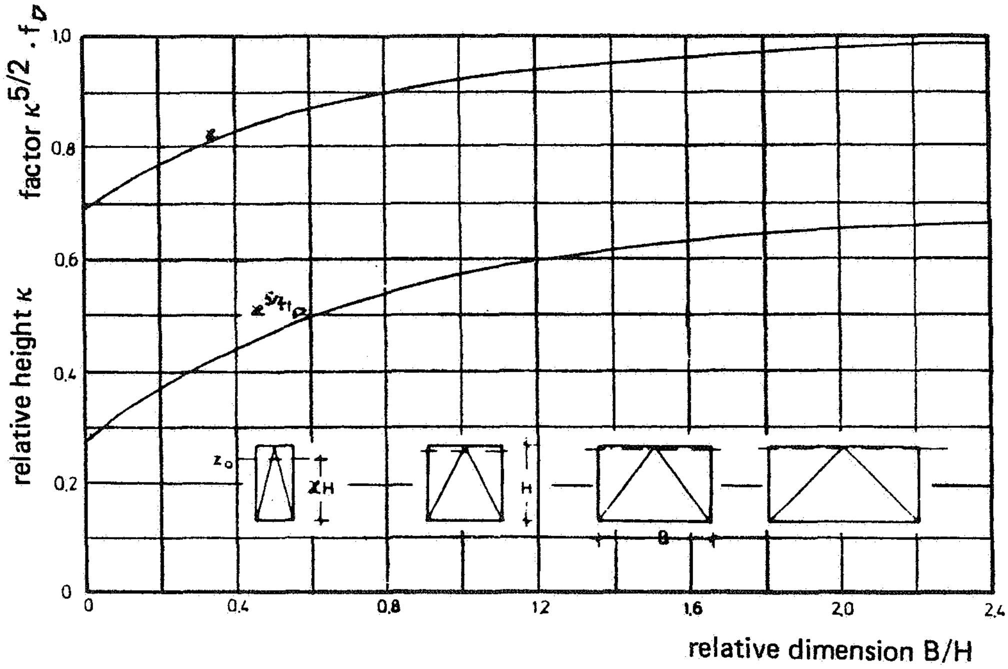


Fig. 20 : Neutral axis $\kappa \cdot H$ and factor $\kappa^{5/2} \cdot f_\nabla$ as a function of relative dimension B/H of pivoted window ($f_\nabla = 0.7$)