AIR CIRCULATION IN BUILDINGS BY THE FLOW IN NETWORKS METHOD

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Introduction

Changes in both the numerical values and proportions of building parameters made with up-to-date construction methods and structures controlling the energy transfer fundamentally altered the respective role of doors and windows, responsible for most of the energy transfer of the buildings.

Energy exchange may have different forms both in winter and in summer such as heat transfer by transmission, thermal exchange by radiation, and air infiltration. Transmission and radiation heat transfer depend on the properties of the structure of doors and windows, but infiltration depends on features of the entire building as a coherent, homogeneous aerodynamic structure, hence it is more difficult to compute. The following will be a short description of the method of computing the infiltration rate of air, and the conclusions drawn therefrom.

Infiltration air circulation is due to the combined effect of three factors such as:

— pressure difference due to wind (between windward and leeward sides),
— stack effect,
— auxiliary mechanical ventilation.

The wind effect, stochastic in character, is of different rate for rooms with similar topological relation, because of orientation.

Also the stack effect varies stochastically. Probable durations of various outdoor temperature intervals are known.

Stack effect and wind are in a weak correlation. Auxiliary mechanical ventilation has a theoretically regular effect.

Accordingly,

— infiltration air circulation depends on several parameters;
— in the heating season, infiltration air circulation undergoes complex variation due to practically independent factors;
— infiltration air circulation changes differently in different rooms, and on different storeys.

Computation of infiltration air circulation involves the fundamental difficulty that the building as a complex aerodynamic object contains great many complex, multiply looped circuits. Designing reckoning with the effect and interaction of all windows, outer and inner doors, stacks and ventilating equipment needs an analog or digital computer. Design for typical weather conditions encountered in heating seasons permits to determine the infiltration air circulation, and thereby the heat demand of ventilation. Methods have been published for determining the window infiltration coefficient and the pressure distribution around buildings.

Computation fundamentals

Our method developed for computing infiltration air circulation is based on the flow in networks, in this case a building and its environment are represented by a graph. The edges represent the topological connections between rooms in the building, the vertices represent rooms as well as some discrete points of the environment. Edges are windows, doors and stacks. This is an illustrative pattern easily matched by designs.

The graph becomes a network upon assigning one or more z_i^k values to each vertex i and one or more $W_{i,k}$ values to each edge i, j, with different meanings as the case may be. In our case, values assigned to vertices are:

— pressure (potential),

— intensity,

and to edges:

— volume flow rate of air (flow),

— laws of conduction (or resistance).

The pressure value is given as overpressure referred to the atmospheric pressure.

Pressure value in vertices representing discrete points of the outer environment is fixed. Pressure has to be computed in vertices representing rooms.

Vertices representing the environment are generally drains or sources, with no fixed or limited intensity. Intensity informs of whether the given vertex is a source, a drain or it is inert.

Intensity is fixed at zero at vertices representing the rooms. The vertex is inert: volume flow rates of air entering and leaving the room are equal.

Volume flow rate of air on each edge can be computed in knowledge of pressure difference and of the law of conduction (or resistance) with the only stipulation to be strictly monotonous increasing, otherwise it is arbitrary and may be different for each edge. General form of the law of resistance for an edge:

$$P_i - P_j = R_{i,j}(f_{i,j}, P_i, P_j), \tag{1}$$

where:

P — potential (pressure),
R — resistance function,
f — flow (volume flow rate of air).

The network has to meet Kirchhoff's first (nodal) and second (loop) laws.

There is a flow $f_{i,j}$ in the network if the difference between flows arriving at and leaving all the vertices equals the intensity:

$$\sum_i f_{i,j} - \sum_j f_{j,i} = d_i \,. \tag{2}$$

Mathematically speaking, an optimum flow minimizing some objective function interpreted on the flow has to be determined. Assigning so-called cost functions $c_{i,j}(f_{i,j})$ known from transport problems to each edge, the problem is to determine flow $f_{i,j}$ meeting the above conditions and minimizing objective functional $\sum c_{i,j}(f_{i,j})$. Necessary and sufficient condition of an optimum flow to exist, in case of functions differentiable everywhere:

$$\begin{aligned} P_i - P_j &\geq c'_{i,j}(f_{i,j}), \qquad & f_{i,j} &= 0 \\ P_i - P_j &= c'_{i,j}(f_{i,j}), \qquad & f_{i,j} &> 0 \,. \end{aligned} \tag{3}$$

Introducing notation:

$$c'_{i,j}(f_{i,j}) = R_{i,j}(f_{i,j}) \tag{4}$$

yields:

$$c_{i,j}(f_{i,j}) = \int R_{i,j}(f_{i,j})\, df \tag{5}$$

hence, for the given physical problem the "cost function" is the so-called dissipation work spent by flowing air to overcome resistance. Objective function yields dissipation work for the entire network, its minimum corresponds to the equilibrium condition.

Computation algorithm can be established by means of the method of dual gradients known from the theory of transport problems. Computer programs have been developed for two types of computer. Principal conclusions drawn from the about 100 designs made to now partly for practice and partly for research will be presented below.

Effect of building topology on the infiltration air circulation

Heat transfer by infiltration is function of the building layout, the architecture and the storey number. The more important it is, the lower the building heat loss by transmission, hence the better the thermal insulation.

A smaller part of transmission heat loss of rooms with poor insulation or with great cooling surfaces results from infiltration heat transfer, thus — in spite of an important heat flow by absolute value — infiltration heat transfer variation involves minor design and control problems. In case of well insulated buildings, however, infiltration heat transfer is high compared to the transmission heat loss, stressing design, control problems related to its variation. Under no-wind conditions, the infiltration heat transfer of several rooms in the test buildings was as high as 80 to 100% of the transmission heat loss ! In general, heat transfer in living rooms is about 50% of the transmission heat

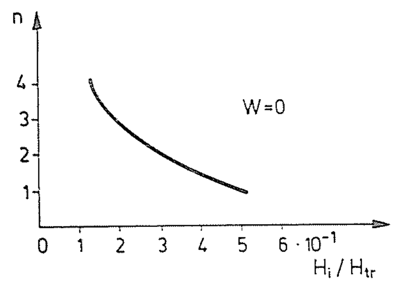

Fig. 1

Legend to figures

H_i	infiltration heat loss
H_{tr}	transmission heat loss
n	storey number
t_0	outdoor temperature
$\bar{t}_0$	outdoor mean temperature
w	wind velocity
w_d	design wind velocity

loss. About this value, there is of course an important scatter according to both building types and storey numbers. In low-rise houses, flats on each storey receive outer air, a phenomenon also connected with the exhaust ventilation in kitchens, toilets and bathrooms. For greater storey numbers, stack effect overrules exhaust ventilation to a degree that flats on upper storeys receive air from the staircase, as seen from diagrams made at an outdoor temperature $t_0 = -15°$ C and calm (Figs 1, 2). In four-storey houses there is only flow in; flats in ten-storey buildings are likely to receive staircase air from the eighth or ninth storey upwards, while in sixteen-storey buildings, "regular" development of the neutral plane is seen.

Beside exhaust ventilation, development of a neutral plane is also much affected by the quality of doors and windows. Better doors and windows raise or cancel at all the neutral zone: gravity-induced air circulation is less, at a fixed exhaust air volume.

The flow pattern much depends also on the number of flats on each storey. Namely, every flat contains kitchen, bath, toilet, hence, with many single-room or one-and-a-half-room flats on a storey, there is a big exhaust air volume, offsetting the stack effect.

The less the building depth and the more articulated the ground plan outlines, the more the wind influences the infiltration heat transfer. Comparing the model buildings it can be stated that the wind effect was reacted on the most sensitively by the building with a little depth and vice versa. Other

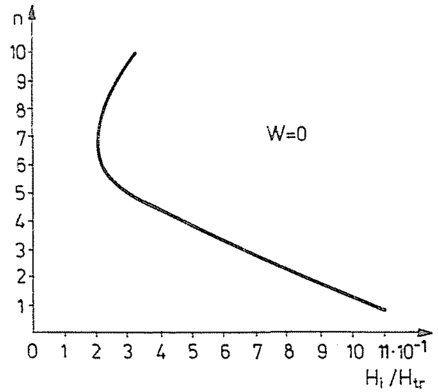

Fig. 2

conditions being equal, the infiltration heat transfer of the former changed three times as much upon wind effect as that of the latter. Ground plans where staircases join long corridors each storey with windows in different façades are unfavourable. Also articulated ground plans worsen sensitivity to wind of infiltration heat transfer of some unfavourably oriented rooms as shown by several examples. Of course, sensitivity to wind depends on the storey number, on the wind velocity and on the shielding of lower storeys.

Better doors and windows much reduce sensitivity to wind. This is of importance not only by reducing heat demand in windy wheater but also because of the poor correlation between wind and outdoor temperature, contributing to ease regulation difficulties and to reduce overheating due to regulation deficiencies.

Serious regulation difficulties are due to the variation of infiltration heat transfer as a function of outdoor temperature. Both stack effect and variation of temperature difference can be considered as linear but the law of resistance is of a character to cause the air mass flow to vary exponentially. Computations show the infiltration heat transfer to decrease as an average with increasing outdoor temperature, and the diagram to be of steeper ascent, the neutral plane to rise or to lack (at a relative increase of the exhaust ventilation effect). Higher wind velocities being more frequent at higher outdoor temperatures, the worsening regulation difficulties stress the upgrading of doors and windows.

Effect of door and window quality on infiltration air circulation

Efficiency of improving the doors and windows much depends on the building they are used in, practically found to result in 17 to 29 per cent of saving in infiltration heat transfer of living rooms (assuming no wind: wind effects increased the relative savings). Saving depends on whether — as outlined above — a neutral zone develops or not. Namely, in rooms about the neutral zone, door and window improvement is inefficient. This is of course by no means to mean that here no better doors and windows are needed, since development and emplacement of the neutral plane are continuously changing depending on the outdoor temperature. Attenuating the wind effect and the control difficulties is sufficient in itself to justify better doors and windows.

The effect of reducing the draught through doors and windows is also offset by exhaust ventilation in kitchens, baths, toilets. Of course, for a given exhaust air volume, theoretically reducing the air transmission through doors and windows beyond all limits, still at least the exhaust air volume has to enter the flat somewhere. Thus, saving possibilities are less where there are many small flats on the same storey.

Halving the air infiltration coefficient of the entrance door alone already results in an appreciable saving of infiltration heat transfer, of each living room rather than of the staircase alone: infiltration air circulation in the building decreases, and so does the air volume getting from the staircase to flats. This effect is counteracted by windows of the staircase, by lift engine rooms with penthouse exits, and by refuse shoots. Improving the entrance hall doors of test model buildings resulted in 5 to 14% savings in the infiltration heat transfer of the building.

Difficulties of designing heat capacity and regulation of identical rooms on different storeys depend on the combined effect of stack effect and exhaust ventilation: the more the infiltration heat transfer varies with the storey, the more difficult these problems are to solve.

Not only the stack effect increases with the storey number but also the variability of heat transfer according to storeys, and the higher the storey number, the less this variability is accessible to improvement by better doors and windows. Thus, heating system design is best differentiated according to storeys.

Infiltration air circulation as a heating system design value

Computer outputs for different meteorological conditions show

— infiltration heat transfer not to be proportional to outdoor temperature either in absolute value or by distribution character;

— the maximum absolute value of infiltration heat transfer not to occur under extreme conditions (t_0 = —15 °C, design wind velocity) for each flat, hence it is not always safe to start from extreme conditions;

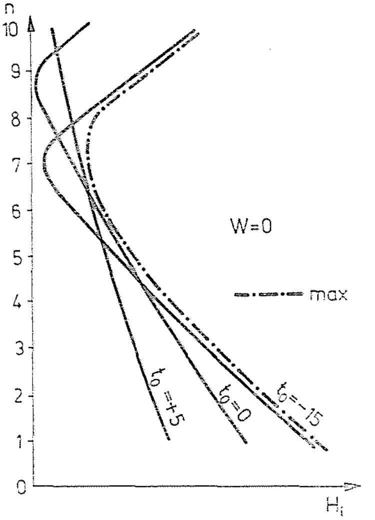

Fig. 3

— the phenomenon of the absolute infiltration heat transfer value of higher flats to increase for higher outdoor temperatures to be considered, especially for high and medium rise buildings likely to develop a neutral plane under extreme conditions, thus maxima can be determined by the presented method of constructing envelope curves for results computed for different conditions. Infiltration heat transfer of each room varies differently as a function of meteorological conditions (Figs 3 to 14).

Therefore, even the most exact design may exhibit a single outside condition where heat demand and built-in performance perfectly agree. In any other case, heat demand proportions are biased so as to result in regular deviations between demand and performance, resulting in overheating and in power consumption excess of 25 to 30%.

This excess consumption can be halved by designing for the most frequent condition. A typical consequence will be for the neutral plane — in any extreme condition — to rise or to vanish with increasing outdoor temperature.

Thus, a frequency-based design reduces the magnitude and duration of indoor temperature differences between storeys. Economically operating heating systems can only be designed by starting from the frequency of outside conditions: replacing "performance-centric" by "operation-centric" approach. Heating and ventilating system of a dwelling house is no bridge to be designed against collapse at high safety for extreme cases but a machinery expected to operate at its optimum under usual conditions, permitted to behave poorer under extreme conditions of infrequent occurrence.

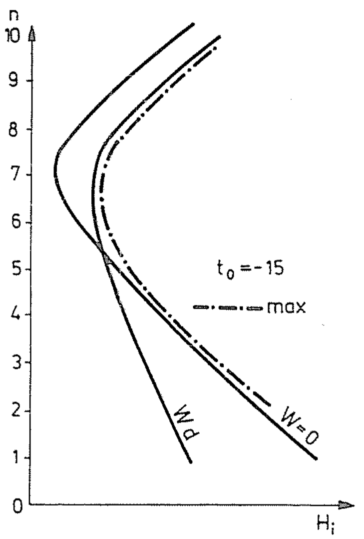

Fig. 4. Leeward side

Infiltration heat transfer of ground floor and lower-storey rooms has its maximum at the lowest outdoor temperature. The expected minimum of outdoor temperature ("design temperature") occurs for a very short time concluding cooling periods, caused by weathering processes accompanied normally by wind. Wind velocities are high at the beginning of cooling periods to gradually decrease. By the end of cooling periods — at outdoor temperature minima — wind velocities are as low as 2 m/s or even below. Thus, infiltration air circulation is due primarily to stack effect and accessory ventilation. Even for single-storey buildings, however, windward and leeward sides have to be distinguished. Namely on the windward side, maximum infiltration heat transfer pertains of course to the design wind velocity for the expected temperature minimum, but on the leeward side mostly to the calm.

In occurrence of the expected temperature minimum and calm, the so-called neutral plane may develop as a function of storey number, number of flats on a storey, and of ground plane features of the building. In this condition, the storeys in and near the neutral plane have a low infiltration heat transfer. Even, if no neutral plane develops, infiltration heat transfer may be distributed among storeys so as to be low in the top. Variability of the infiltration heat transfer according to storeys is seen by the slope of lines in the diagram.

With varying outdoor temperature also the curve slope varies to a degree depending on the effect of accessory ventilation, shifting the neutral plane upwards. (Even, if no neutral plane develops within the building height,

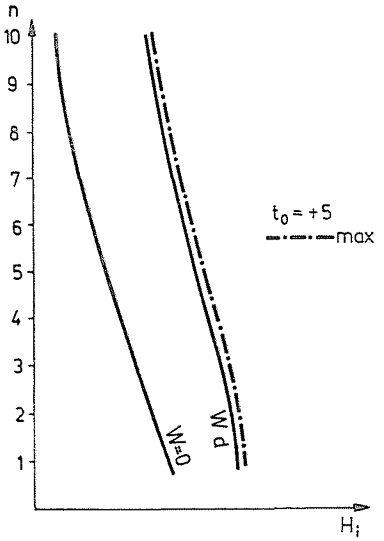

Fig. 5. Windward side

the phenomenon can be imagined by starting from a point in the curve of zero air mass flow.) Identity between outdoor and indoor temperature results in a vertical straight-line diagram.

According to the precedings, infiltration air mass flows vary so that rooms in or near the neutral plane for, e.g. $t_0 = -15°$ C get below it for higher outdoor temperatures. Thereby changed pressure conditions intensify and maybe deflect infiltration air circulations. (For example, at a lower outdoor temperature, air gets from the staircase into the room, windows exhibit exfiltration, higher outdoor temperatures generate infiltration through windows and cause air to leave through the ventilation system.) In a given case, air circulation may grow faster than thermal difference $(t_i - t_\sigma)$ decreases, hence infiltration heat transfer will grow for increasing outdoor temperatures. Of course, this is not true for the entire range of $t_i - t_\sigma$ during the heating season but only for a given interval.

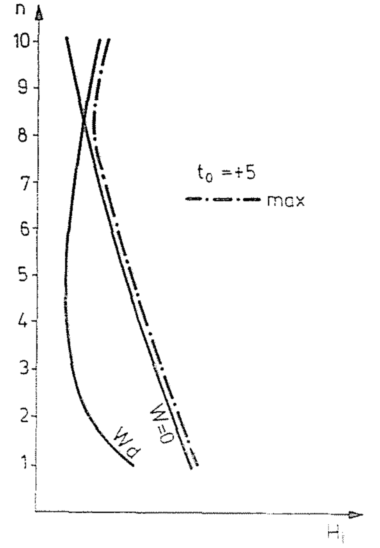

Fig. 6. Leeward side

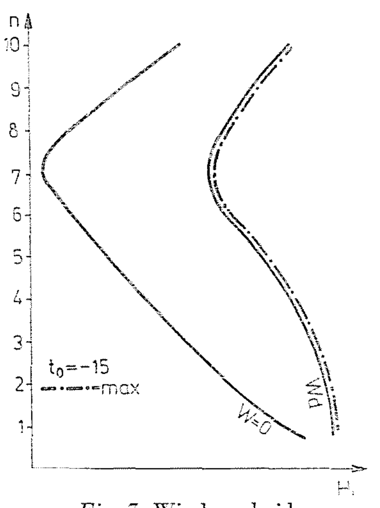

Fig. 7. Windward side

In view of the loose correlation between outdoor temperature and wind velocity, maximum infiltration heat transfer may be stated to occur windward for higher outdoor temperature and wind, and leeward for lower outdoor temperature and calm, an effect of maximum probability for high-rise houses where wind velocity distribution along the height, and thus, the higher wind velocity at higher storeys become prevalent.

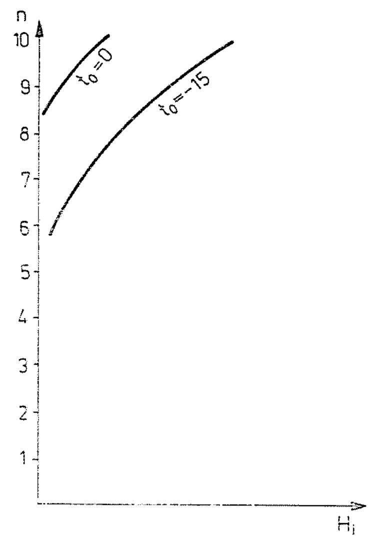

Fig. 8. Entrance room

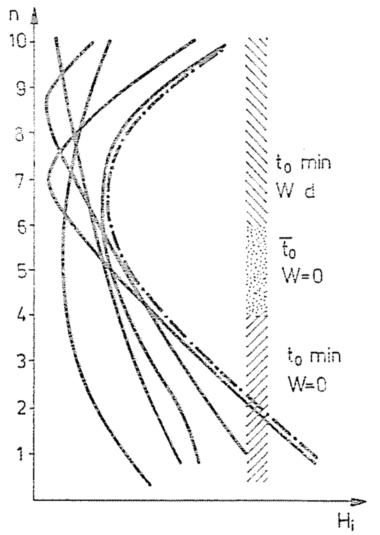

Fig. 9. Leeward side

Complexity of the problem is seen from this short analysis. The high number of involved parameters prevents a generally valid rule from being established; the combined effects show the following tendencies:

The greater the probability for a neutral zone to develop (at $t_{\sigma,\min}$):

— the higher the storey number,

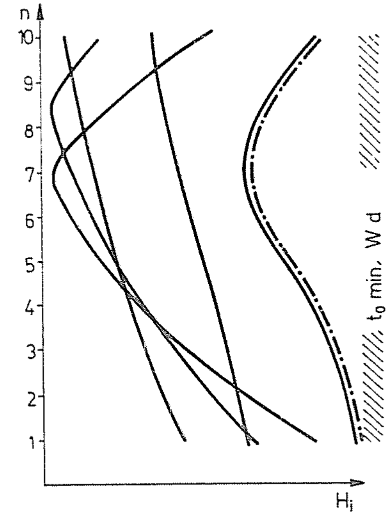

Fig. 10. Windward side

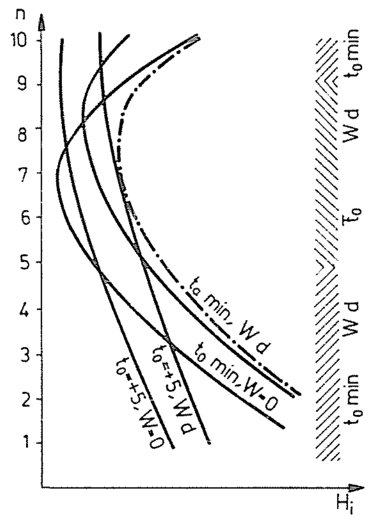

Fig. 11. Windward side

— the less flats there are on a storey,

— the poorer the doors and windows.

For a room much below the neutral plane (i.e. in the lower storeys, if a neutral plane develops within the building height at $t_{\sigma,\min}$; else in any storey)

— infiltration heat transfer has its maximum at $t_{\sigma,\min}$ and this at wind on the windward side, and mostly at calm on the leeward side.

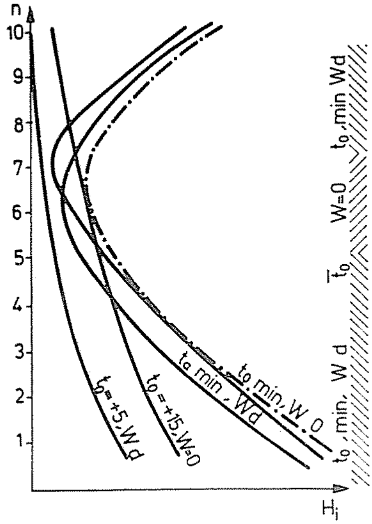

Fig. 12. Leeward side

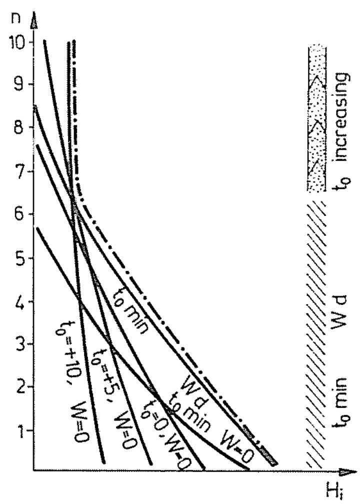

Fig. 13. Room not connected to entrance hall. Windward side

For a room in or over the neutral plane at $t_{\sigma,\text{min}}$

— infiltration heat transfer has its maximum

a) on the windward side at $t_{\sigma,\text{min}}$ or at an outdoor temperature near the average;

b) on the leeward side near the average outdoor temperature.

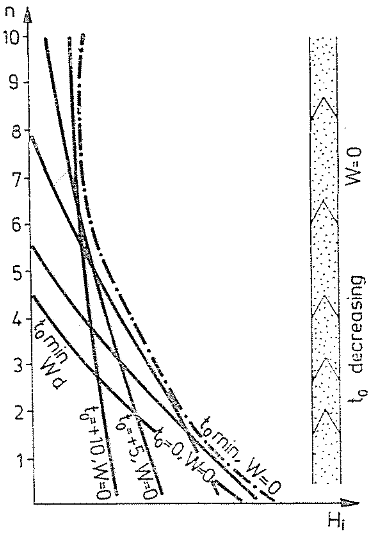

Fig. 14. Room not connected to entrance hall. Leeward side

Summary

Infiltration heat transfer increasingly affects the energy turnover of up-to-date buildings. It depends on a multitude of factors imposing the building to be designed as a unique aerodynamic structure. Analysis of computer results points to the effect of storey number, ground plan features and exhaust ventilation systems. Different rooms exhibit infiltration heat transfer maxima at different outdoor temperatures.

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