AIR MOVEMENTS IN BUILDINGS

Magnus Herrlin
The Royal Institute of Technology, Stockholm, Sweden

Abstract

The indoor air quality depends on several different factors. One is the air flows or air movements within the building and through its external walls. These flows are governed by the type of leakage openings and the pressure differences across the walls and the air terminal devices. The pressure differences are caused by wind, thermal and fan forces. Mathematical models can be used to calculate the different air flow rates. A simple example is used to demonstrate magnitude and consequences of this air leakage for two different ventilation systems. Finally a recent survey of computer programs is reviewed. No program, which calculates the air flows in detail, was found to be available.

Introduction

The indoor air quality mainly depends on:

- the production of contaminants within the room
- the air movements within the room
- the production of contaminants within adjacent rooms and the outside air quality
- the air flows within the building and through its external walls.

Contaminants in outdoor air is transported into the building with infiltrating air and ventilation air. Contaminants produced within the building is spread to other rooms by the air flows within the building. These flows consequently are significant for the indoor air quality.

Forces causing air flows in a building

The air flows in a building, i.e. in/exfiltration and inter-room air flows are caused by wind, thermal and fan forces.

The windforces are the most complicated to estimate. The corresponding pressures, positive on the windward side of the building and negative on the leeward side vary continuously, due to turbulent wind. The magnitudes of the pressures depend on the height over the ground and on surrounding landscape and buildings. The pressure differences cause unsteady

flow through the leakage openings. A common simplification under estimating flow rates is to consider the wind as steady. Wind pressures then can be calculated as:

$$p_v = C_p p_d = C_p \frac{1}{2} \rho v^2$$

where

p_v = wind pressure (Pa)

C_p = pressure coefficient (-)

p_d = dynamic pressure (Pa)

ρ = air density (kg/m^3)

v = wind velocity (m/s)

The thermal forces are due to temperature differences between inside and outside air. The corresponding pressure difference is:

$$\Delta p = (\rho_{out} - \rho_{in})\ gh$$

where

Δp = pressure difference (Pa

ρ_{out} = outside air density (kg/m^3)

ρ_{in} = inside air density (kg/m^3)

g = gravitational constant (m/s^2)

h = height between openings (m)

An airflow is developed, which enters the building in the lower parts and leaves it in the upper floors.

The mechanical ventilation system can be disturbed by wind forces and thermal forces. These forces may be seen as "fans" in series with the fan, either assisting or opposing it. If the system is designed for high pressures then the airflows are more stabilized.

The fan forces depend on the type of fan and the type of ventilation system. There are several types of fans with different relationship between air flow rate and pressure. There are also different types of ventilation systems, mainly exhaust and exhaust/supply systems.

A well designed system is characterized of its speed to take away as well as not to supply contaminants. When designing a ventilation system one must take the building into consideration since a system which is good in one type of building may be a bad one in another.

Flow equations

The air flows also depend on the leakage openings and the air terminal devices. Therefore, it is of greatest importance to know the flow equations, i.e. the relationship between the pressure difference and the air flow rate, for different leakage openings and air terminal devices. The air flow rate is often approximated as:

$$\dot{m} = K\,(\Delta p)^n$$

where

$\dot{m}$ = mass flow rate (kg/s)

K = flow coefficient (kg/s, Pa^n)

Δp = pressure difference across an opening (Pa)

n = flow exponent ($0{,}5 \leq n \leq 1{,}0$)

Cracks around windows and doors mostly have an exponent in the range 0,6 - 0,7, while air terminal devices have an exponent of 0,5.

Mathematical models

The forces and the flow equations can be used to compute the air movements in the building. The building is divided into "rooms", physical or imagined. A "room" is defined as a space with just one pressure in a horizontal plane. Therefore each room can be represented by a pressure node. These nodes are connected to each other through the leakage openings. Figure 1 shows two types of "networks". The left one belongs to a single-cell model, while the right one belongs to a multi-cell model. For the sake of clearness the ventilation system has been given out. In the single-cell model the assumption has been made that the indoor separations are of small importance to the air movements. With such a simple model, the inter-room air flows cannot be studied. The multicell model takes the indoor separations into consideration. Therefore, such a model is more complex and can be used in many different applications.

Each room in the entire building must have a mass balance (steady-state) i.e. the incoming mass flow rate must be equal to the outgoing mass flow rate. These rates can be expressed as flow equations. In a multicell model a system of equations has to be set up, where the unknown internal pressures, one in each room, can be solved, if the pressures outside the building are known. As has been described above these pressures can be estimated. The system of equations is non-linear and has to be solved by an iterative method, i.e. assumed pressures are revised gradually until a satisfactory balance is obtained. The following example demonstrates the usefullness of a mathematical model.

Example

The air quality is of greater importance in hospitals than in most other buildings. The example is a floor in such a building. All rooms along the corridor are equal as in Figure 2. Desired directions of the airflows within the building can be different depending on the application of the rooms. The example assumes rooms with patients without infectious diseases. Desired directions of the airflows can be from the rooms to the corridor, since this gives the possibility to keep a higher air quality in the rooms. The wind direction is perpendicular to the left external wall, according to Figure 2. Undesirable air flow can therefore be expected to appear between the corridor and the right room. The most interesting flow is the flow between these two spaces, both the rate and the direction.

The intention with a so-called balanced ventilation is that every room should be a unit, i.e. air movements between the room and adjacent rooms are prevented. The mechanical ventilation and its nominal flow rates in the upper part of Figure 2 are according to the Swedish Building Code, 1980, as well as the flow coefficients. The diagram to the right shows the computed leakage flow rate between the corridor and the right room, q_A, as a function of the wind velocity.

The positive directions of the flows due to the wind-forces are defined in the figure. The average wind velocity in Stockholm is approximately 3 m/s. The corresponding leakage flow rate is about 4 l/s which is 10 % of the supply flow rate to the room. 5 % of the time, the wind velocity exceeds 7 m/s, so this can be seen as the highest velocity to be taken into consideration. The corresponding leakage flow rate is almost 13 l/s or about 30 % of the supply flow rate. It is obvious that this "balanced system" never can be expected to maintain the room as a ventilation unit during normal conditions.

The lower part of Figure 2 shows the nominal flow rates with a modified type of balanced ventilation system. The exhaust air in the corridor is supplied from the rooms. This system is not strictly in accordance with the Swedish Building Code. As can be seen, the flow direction is from the right room to the corridor when the wind velocity is less than 4 m/s. In this velocity range, the room is "isolated" i.e. no contaminants can be brought to the room from the corridor. This modified balanced system keeps the desired air flow directions better than the system above, according to the graphs in the diagram.

The supply and exhaust flow rates change of course when different forces are acting. In this example, however, the changes are neglectable.

The general conclusion of this example is that the distribution of the exhaust- and supply air flow rates within the buildings is of the greatest signification to maintain desired airflow directions between the rooms during normal conditions.

Computer programmes

As have been showed above, a mathematical model can be used to study different ventilation systems to obtain the best function, defined according to a criterion. A computer is however needed to solve the non-linear equation system and to handle all data that is required for a multi-cell model if a result is wanted in a reasonable time.

Several computer programmes have been developed during the past 20 years. A validation and comparison of some of these programmes have been made at the Air Infiltration Centre (1). Recently, a survey has been made at the Division of Building Services Engineering at the Royal Institute of Technology. Seven multi-cell programmes are described in the report "Luftströmning i byggnader" (Air movements in buildings) (2). There are two main differences between the programmes. First, the possibility to simulate the ventilation system in detail i.e. ducts and fans. Secondly, the possibility to describe the building with an arbitrary "network", i.e. the connections between nodes. The table below shows roughly the comparative capacities of the seven different programmes in these two matters.

The left part shows the possibilities of different models to simulate the ventilation system. As can be seen, there are three main groups. Within a group the programmes are in alfabetical order. The top "group" can handle both fan- and duct characteristics i.e. this program is almost quite general. The next "group" can only take the fan characteristics into account. This type of simplification can be useful. The remaining models cannot take the room pressure into consideration and calculate the ventilation system flows. These flows have to be constants. This has to be considered as a rough simplification in many applications.

The right part of the table shows the possibilities for the programmes to handle an arbitrary network. The models at the top do not have any serious limitations. The programme DBR-37 demands a building model, represented by a set of compartments stacked one on top of another and by a set of shafts that pass through all the compartments. This, of course reduces the usefulness of the model.

Table 1. The comparative capacities of seven multi-cell programmes

Ventilation system	Network
STROM	ELA 4
SWIFIB	LEAKS
DBR-37	STROM
ELA 4	SWIFIB
LEAKS	TARP
TARP	VENT 1
VENT 1	DBR-37

DBR-37* (3)	National Research Council of Canada, Ottowa, Canada
ELA 4	Institut voor Milieuhygiene en Gezondheidstechniek, Delft, Holland
LEAKS	The Building Services Research and Information Association, Bracknell, England
STROM	Technische Universität Berlin, Berlin, W-Germany
SWIFIB	The Oscar Faber Partnership, St. Albans, England
TARP* (4)	National Bureau of Standards, Washington DC, USA
VENT 1	British Gas Corporation, London, England

* Available

Unfortunately, most of these programmes are not available, i.e. they may not be used outside the companies. The reasons may be either that the programme is still developing or commercial points of views. The programmes marked with an asterisk are available. As can be seen these two are not very flexible. Therefore, a project has recently been started at the Royal Institute of Technology to develop a computer model, suitable to study the air movements in buildings and the airflows in ventilation systems. The programme should have the capability to simulate an arbitrary ventilation system as well as an arbitrary building.

References

1 LIDDAMENT, M, ALLEN, C
The validation and comparison of mathematical models of air infiltration. Technical Note AIC 11, Bracknell, England, 1983.

2 HERRLIN, M
Luftströmning i byggnader. Tekniskt meddelande nr 268, Institutionen för uppvärmnings- och ventilationsteknik, Tekniska Högskolan, Stockholm, Sweden, 1983.

3 SANDER, D M
Fortran IV program to calculate air infiltration in buildings, DBR computer program no 37. National research council of Canada, Ottawa, Canada, 1974.

4 WALTON, G N
Thermal Analysis Research Program Reference manual, NBSIR 83-2655. National bureau of standards, Washington DC, USA, 1983.

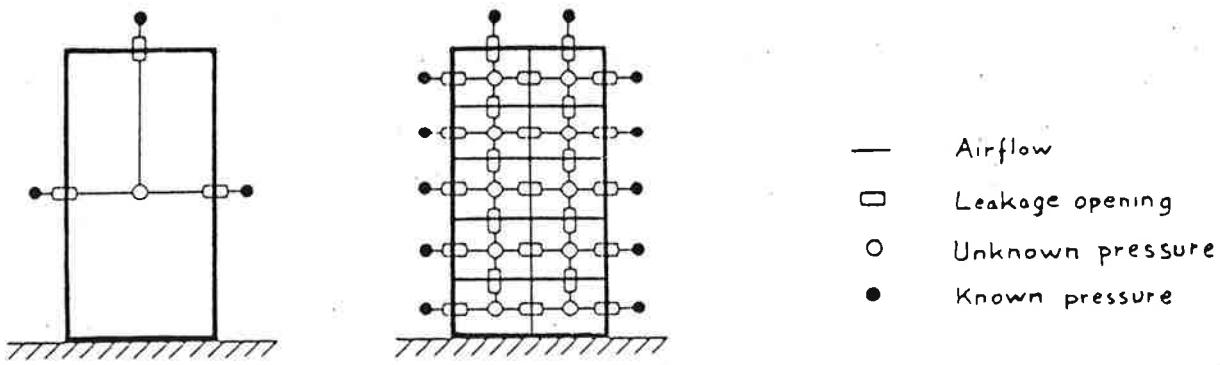

Figure 1. Two examples of "networks".

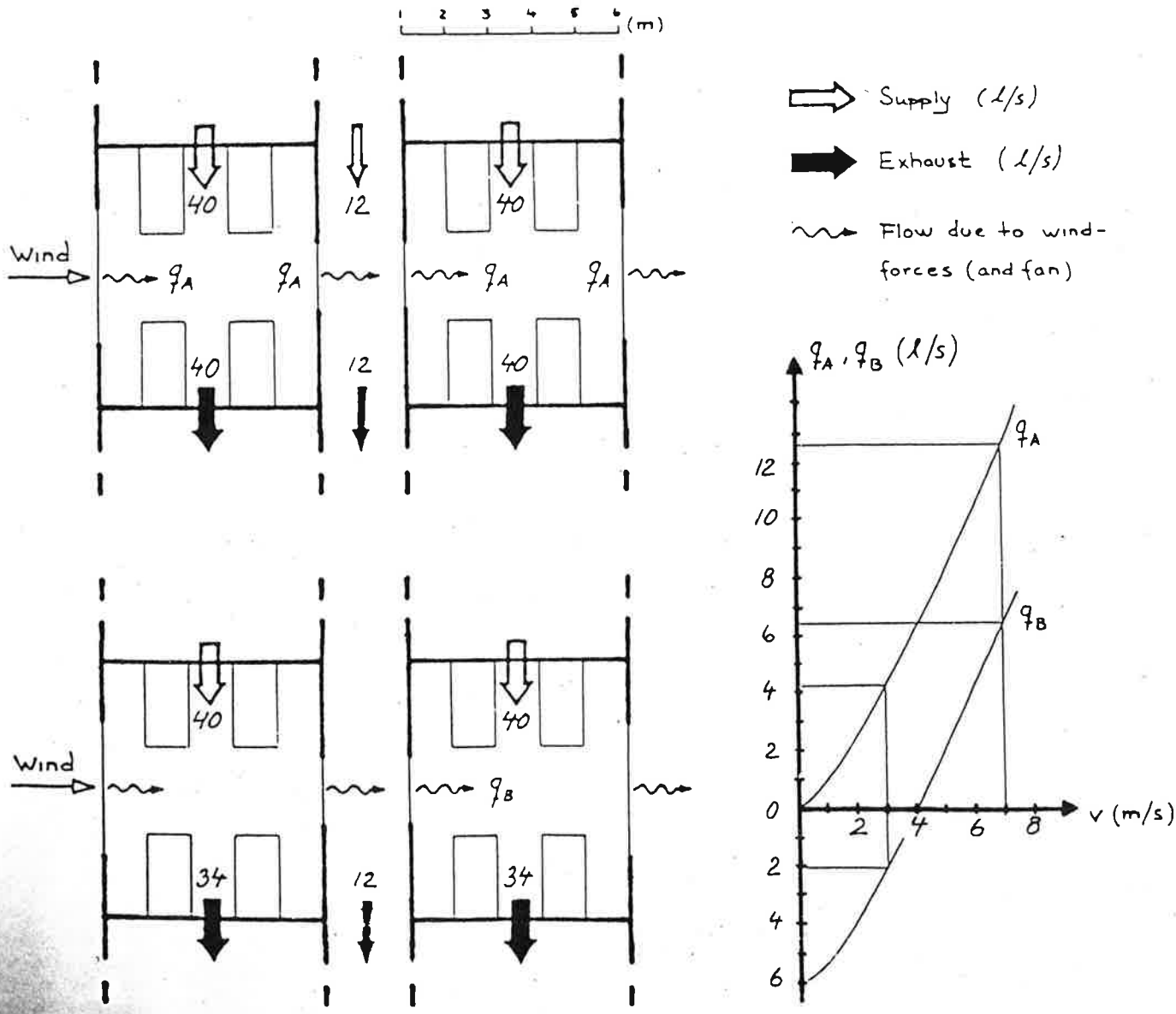

Figure 2. The configuration of the rooms and the nominal flow rates. Calculated rates to the right.