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by

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(Metod för bestämning av luftströmningen inom byggnader)

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METHOD FOR MEASURING THE AIR FLOW IN BUILDINGS

by Hirochi Honma

The article describes a method for measuring the direction and volume of air flows in a building with several rooms. The method is based on tracer gases and gas producing equipment is used in each room. During a period of 2 - 3 hours the concentration of gas is measured in each room every 10 minutes. By means of a dator the direction and flow between rooms can then be calculated. The method is based on an investigation started at the Hokkaido University at Sapporo, which was continued at the Institute for Heating and Ventilation, KTH. Part of the material for the latter part of the work was supplied by the Government Institute for Building Research.

The air flow between rooms in a building can be directed by maintaining pressure differences between the rooms and by a suitable choice of excess flow equipment.

However, the basis for projections to obtain specific flow conditions is uncertain for many applications. Factors which play a part but which can only be considered in exceptional cases are, for instance, excess flow by doors and unintended ventilation through gaps. In both cases unforeseen temperatures and pressure differences can create considerable ventilation often in an unfavourable direction from the point of view of the building.

So far the uncertainty of calculations of the above kind has not been studied more closely, mainly because measuring techniques have been lacking for the accurate determination of air flows and directions.

The method described here is an attempt to fulfil this need. It is expected to be widely used in a range of ventilation fields.

* The method permits objective comparison between different ventilation systems.

* It can be used for the estimation of the risk for spreading damaging air pollution from other rooms.

* In hospitals, for instance, there is a great risk of the spreading of diseases through the overflow of air between wards. The method can be used for the calculation of such risks.

* The degree and position of involuntary ventilation can easily be determined for a part or the whole of a building.

* The degree of ventilation achieved in a building can be compared with the projected ventilation and, if necessary, an adjustment can be determined.

* The effect of weather, inside temperatures and activities on the ventilation in a building can be determined.

The method is based on tracer gas measurements. Carbon dioxide, CO_2, which is easily obtainable by the evaporation of dry ice, is used as a tracer gas.

Equipment, see fig. 1, with a controllable production of CO_2 is used in each room. The apparatus contains an electric heater for the evaporation. A few pieces of dry ice are placed on the warming plate and the gas production is adjusted by effect regulation. The production of gas during each measuring period must be calculated in each case independently of the others.

The connection between the gas production and heat supply is shown in fig. 2. Analytically the production can be written as follows, which is sufficiently accurate for our purpose:-

$$I(\tau) = U(1 - e^{-B\tau}) \qquad (1)$$

where I is the production of gas (Kg/Ws) which is a function of the time τ(S).
U is the gas production per added heat unit, (kg/Ws).
B is a constant determined, for instance, by the heat capacity of the equipment. The unit for B is (s^{-1}).

If an effect variation is applied according to fig. 3, it is possible by adding the solutions of equation (1) in the case of each change in rise to determine the production, $W(\tau)$ of the gas during the period τ.

It may be appropriate here to remark on a source of mistakes. Heat penetrating the insulation does result in some gas production. The heat effect is called A_o in the fig. and is treated separately.

In the case of the apparatus shown in the fig., the following applies in normal circumstances:-
The production of gas, $W_o$kg/s is 0.04 - 0.05 x 10^{-3} kg/s.
U = 1.15 - 1.25 x 10^{-3} kg/Ws.
B = 3.0 - 4.0 x 10^{-3} s^{-1}.
The value of W_o depends, for instance, on the quantity of dry ice. To achieve even conditions a sufficient amount of ice should be used. All tests should be started with about the same amount of dry ice, and the experiments should not be carried out any longer, when a certain amount of ice remains at the end of the test period.

Carbon dioxide is about 1.5 times heavier than ordinary air and there is therefore a risk that the gas remains in layers in the room.

In a series of experiments the homogenous character of the gas distribution was estimated in a room. In the first experiment the gas was allowed to escape from the outlet of the equipment without a fan. The variations in concentration at five different heights during each hour are shown in fig. 4. The differences in concentration between the higher and lower measuring plane in this test series is clearly shown.

In another test series the gas was heated above the room temperature at the outlet of the apparatus so that the above mentioned difference in density between the air and gas was reduced. The concentration at a higher level increased with an increased concentration, the greater the distance from the floor, see fig. 5.

In a third experiment the gas was mixed with large quantities of air from the room by the outlet, and the gas was also blown upwards by a fan. Fig. 6 shows the variations in concentration at four different levels. The result showed an essentially more even distribution of concentration compared with the result of previous tests.

In the deduction of the calculation method used it may be practical to look at the next example, see fig. 7. The picture shows a part of a building consisting of four rooms. The flows between the rooms are indicated by ν_{ij} when the flow goes from room j to room i. The flow to the surroundings (which is considered as having one and the same concentration, C_o(kg/c.m.), of the tracer gas) is described as ν_{oi}. The total flow from a room is described as ν_{oi} ($\nu_{oi} = \nu_{o1} + \nu_{21} + \nu_{31}$ in fig. 7).

If the concentration in each room at the time τ_1 and the time τ_2 and the gas production in room 2 during the corresponding period are known, the gas concentration in room 2 can be calculated as $C_{22} \cdot V_2 = C_{12} \cdot V_2 + W_2 \cdot \Delta\tau + (C_{11} \cdot \nu_{21} + C_{13} \cdot \nu_{23} + C_o \cdot \nu_{20} - C_{12} \cdot \nu_{02}) \cdot \Delta\tau$ (2)

where $C\tau_i$ is the gas concentration (kg/c.m.) in the room i at the time τ.
V_i is the volume of room i (c.m.)
$\Delta\tau$ is the time interval (s) between τ_1 and τ_2, $\Delta\tau = \tau_2 - \tau_1$
W_i is the gas production (kg/h) per hour in room i
ν_{ij} is the air flow (c.m./h) from room j to room i

The equation can be applied to every time interval and the equation system obtained can be treated as linear on condition that

* the measurements of the concentration in each room take place at short intervals, and

* that the changes in concentration in each interval can be regarded as linear in time.

The solution to the system gives the air flows, and every flow in the house can be calculated by applying the continuity condition room by room.

However, if the interval between the measurements is too long, and the concentration changes during the intervals cannot be regarded as linear, the changes must be regarded as transient. For room, k, according to fig. 8a, (2) changes into a differential equation:

$$Vk \cdot \frac{dC\tau_k}{d\tau} + \nu\sigma_k \cdot C\tau_k = W\tau_k + \nu_{ko} \cdot C_o \qquad (3)$$

The concentration $C\tau_k$ in room k can be obtained by intregrating equation (3) and with the gas production expressed by an equation.

In the case of several adjoining rooms, as in fig. 7, the mass flows are added according to:-

$$V_i \frac{dC\tau_i}{d\tau} + \nu\sigma_i \cdot C\tau_i = W_i + \Sigma_j \cdot \nu_{ij} \cdot C\tau_j + \nu_{io} \cdot C_o \qquad (4)$$

The effect from rooms which are connected with other rooms in more than one way is equal. In such a case it is advisable to treat the effect as a constant expressed as a sum of the concentration in the rooms and the air flows.

The connection (4) for the concentration in the room at the time τ can be expressed as a function of all the air flows which arrive in room i, and the sum of the air flows which leave the room.

The flows are considered as combined of supposed air flows $\dot{\nu}_{ij}$ and corrections ν_{ij}: $\nu_{ij} = \nu_{ij} - \ddot{\nu}_{ij}$ (5)

By using this relationship the concentration in room i and the time τ can be developed as a Taylor series.

The terms which are small of the second order are discarded, which yields a linear equation for the calculation of corrections $\ddot{\nu}_{ij}$.

The linear equation can be set up for each concentration measurement.

In this way the corrections $\ddot{\nu}_{ij}$ can be obtained by means of the least square method.

Generally the supposed values for $\dot{\nu}_{ij}$ are not sufficiently exact so that one can put aside other terms than the quadratic. Thus some kind of formula should be used to obtain better values for air flows ν_{ij}. Such a formula is to repeat the procedure and to reach the conclusion iteratively. Sometimes the solution diverges during repetition. In these cases it is advisable that the correction counteracts the divergence. For this purpose both the following expressions can be put forward. One of them weakens the effect of the correction by the use of a coefficient E_1 in equation (5) according to $\nu_{ij} = \dot{\nu}_{ij} - E_1 \cdot \ddot{\nu}_{ij}$ (6)

The other $-E_2 < \ddot{\nu}_{ij} < E_2$ (7)

limits the correction to a certain extent. The coefficient E_1 should be within the area 0.5 - 1.0; the coefficient E_2 within 2×10^{-3} c.m./s.

Machine program

The above calculations are carried out most conveniently with a data program. The number of rooms in the actual plan of the house and possible flows between rooms can easily be expressed in figures. The qualities of the gas-producing apparatus and the pattern of the heat supply (for each apparatus) then follow. Finally the measured concentration variations in each room are fed into the machine. The final result for the air flows can be obtained after about 30 iterations. It is also possible to obtain a list of middle values.

The variations in concentration in a building according to fig. 7 are calculated with the help of equations as described previously. Table 1 gives the air flows, the qualities of the gas producing apparatus and the pattern for the heat supply for each room. The air flows are calculated by using the concentration variation for each 15th minute. The middle part in the case of the iterative calculations for two sets of starting values are given in table 2a and 2b. The calculations were terminated when the sum of absolute correction values $\ddot{\nu}_{ij}$ had decreased to below 1.0 c.m./h.

The directions of the air flow between two rooms cannot be determined at the start of the calculation. It may also be worth pointing out that a negative flow in the calculation means that the other results have no practical value. In such a case the variations in concentration are calculated as a result of enforced flow, see table 3.

Table 1. List of data to be used when investigating the main program.

a. Air flow between rooms ν_{ij} (c.m./h)
room number j (delivery side)
reception room i

	1	2	3	4	5
1	0.0	10.0	5.0	0.0	50.0
2	35.0	0.0	0.0	10.0	30.0
3	20.0	0.0	0.0	30.0	5.0
4	0.0	60.0	10.0	0.0	10.0
5	10.0	5.0	40.0	40.0	0.0

room no. 5 indicates the outside air

b. Room volume (c.m.)

1	2	3	4
15.0	10.0	10.0	15.0

c. The qualities of the gas-producing apparatus (same for each room).

A_o = 0.200 kg/h

U = 2.000 kg/Ws

B = 2.0 x 10^{-3} s^{-1}

d. Effect supply (W)

time (min)	room no.			
0.0 – 20.0	50.0	0.0	0.0	50.0
20.0 – 40.0	0.0	50.0	50.0	0.0
40.0 – 60.0	50.0	0.0	0.0	50.0
60.0 – 80.0	0.0	50.0	50.0	0.0
80.0 –100.0	50.0	0.0	0.0	50.0

Table 2. The course of the iterative calculation of air flows (c.m./h).

a.

		ν_{12}	ν_{13}	ν_{10}	ν_{01}	ν_{21}	ν_{23}	ν_{20}	ν_{02}	ν_{31}	ν_{34}	ν_{30}	ν_{03}	ν_{42}	ν_{43}	ν_{40}	ν_{04}
starting value		15.0	10.0	30.0	80.0	30.0	10.0	50.0	80.0	25.0	25.0	10.0	60.0	50.0	20.0	20.0	70.0
repetition	$\sum_i \sum_j$ ($\ddot{\nu}_{ij}$)																
5	41.1	12.6	2.3	49.4	66.3	38.2	9.3	27.8	72.4	22.6	27.7	4.9	54.3	58.1	9.7	11.8	81.7
10	7.6	10.3	4.5	50.3	65.2	35.3	10.6	28.6	74.4	20.4	30.3	3.9	54.6	58.9	10.4	11.7	81.1
15	2.3	10.1	4.9	50.1	65.0	35.0	10.1	29.7	74.9	20.1	30.1	4.7	54.9	59.5	10.3	10.6	80.3
18	0.9	10.0	5.0	50.0	65.0	35.0	10.0	29.9	75.0	20.0	30.0	4.9	55.0	59.8	10.1	10.2	80.1
Resulting Value		10.0	5.0	50.0	65.0	35.0	10.0	30.0	75.0	20.0	30.0	5.0	55.0	60.0	10.0	10.2	80.0

b.

		ν_{12}	ν_{13}	ν_{10}	ν_{01}	ν_{21}	ν_{23}	ν_{20}	ν_{02}	ν_{31}	ν_{34}	ν_{30}	ν_{03}	ν_{42}	ν_{43}	ν_{40}	ν_{04}
starting value		5.0	10.0	100.0	100.0	10.1	5.0	50.0	50.0	50.0	0.0	50.0	100.0	50.0	10.0	50.0	50.0
repetition	$\sum_i \sum_j$ ($\ddot{\nu}_{ij}$)																
5	268.4	0.2	16.1	85.0	80.2	25.0	18.0	30.9	69.7	25.0	25.0	40.4	75.0	29.5	35.0	25.0	71.9
10	83.5	9.8	5.5	60.0	65.5	33.2	8.0	34.0	77.5	16.9	28.9	15.4	58.2	54.2	14.1	7.9	75.3
15	13.4	9.8	5.4	49.9	64.8	34.5	9.5	31.7	75.7	18.7	30.5	6.9	55.7	64.1	7.2	6.1	77.9
20	3.6	9.9	5.1	49.9	65.0	35.0	9.9	30.4	75.1	19.8	30.0	5.5	55.2	60.7	9.6	9.2	79.6
24	0.9	10.0	5.0	50.0	65.0	35.0	10.0	30.1	75.0	20.0	30.0	5.1	55.0	60.2	9.9	9.8	79.9
Resulting Value		10.0	5.0	50.0	65.0	35.0	10.0	30.0	75.0	20.0	30.0	5.0	55.0	60.0	10.0	10.0	80.0

Table 3. Supposed air flows (c.m./h).

1	0.0	0.0	5.0	0.0	50.0
2	5.0	0.0	0.0	0.0	30.0
3	40.0	0.0	0.0	5.0	5.0
4	0.0	30.0	5.0	0.0	10.0
5	55.0	35.0	50.0	45.0	0.0

Table 4. (c.m./h).

-	starting value	ν_{12}	ν_{13}	ν_{10}	ν_{01}	ν_{21}	ν_{23}	ν_{20}	ν_{02}	ν_{31}	ν_{34}	ν_{30}	ν_{03}	ν_{42}	ν_{43}	ν_{40}	ν_{04}
		5.0	5.0	20.0	100.0	20.0	10.0	20.0	30.0	10.0	10.0	5.0	100.0	20.0	10.0	5.0	30.0
repetition	$\sum_i \sum_j (\nu_{ij})$																
5	463.3	5.4	27.5	1.0	75.6	2.1	4.6	38.1	37.5	10.0	24.3	12.9	95.0	31.4	3.3	8.4	44.9
10	132.2	2.5	8.2	26.9	53.8	7.8	0.4	27.6	34.0	35.0	7.6	5.0	70.0	31.5	4.5	9.8	44.9
15	14.9	0.8	4.9	47.6	54.5	5.7	0.1	29.4	34.7	41.9	4.5	3.4	50.6	30.5	4.2	11.3	45.7
20	1.7	0.0	5.0	49.9	55.0	5.1	0.0	30.0	35.0	40.2	4.9	4.9	50.0	30.1	4.9	10.2	45.1
22	0.6	0.0	5.0	50.0	55.0	5.0	0.0	30.0	35.0	40.1	5.0	4.9	50.0	30.0	4.9	10.1	45.0
resulting value		0.0	5.0	50.0	55.0	5.0	0.0	30.0	35.0	40.0	5.0	5.0	50.0	30.0	5.0	10.0	45.0

It is found that air flows ν_{12} and ν_{21} do not exist in this case, but that originally they were expected to be 5.0 and 1.0 c.m./h respectively, see table 4. As can be seen from this table, the result of the non-existing air flows is nil.

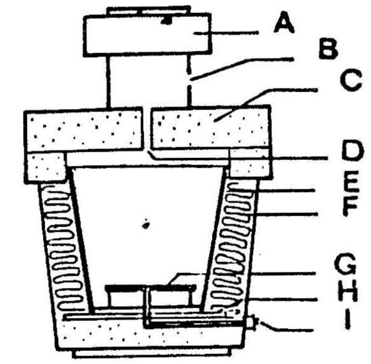

Fig. 1. CO_2—producing apparatus. A = fan, B = air intake, C = plastic insulation, D = carbon dioxide, gas outlet, E = metal cylinder, F = insulation, G = heating element, H = asbestos disc, I = electric connection.

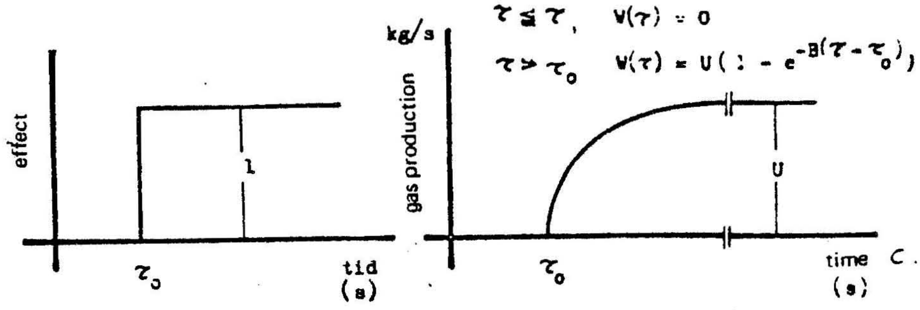

Fig. 2. Sudden effect change and the corresponding change in the produced gas flow.

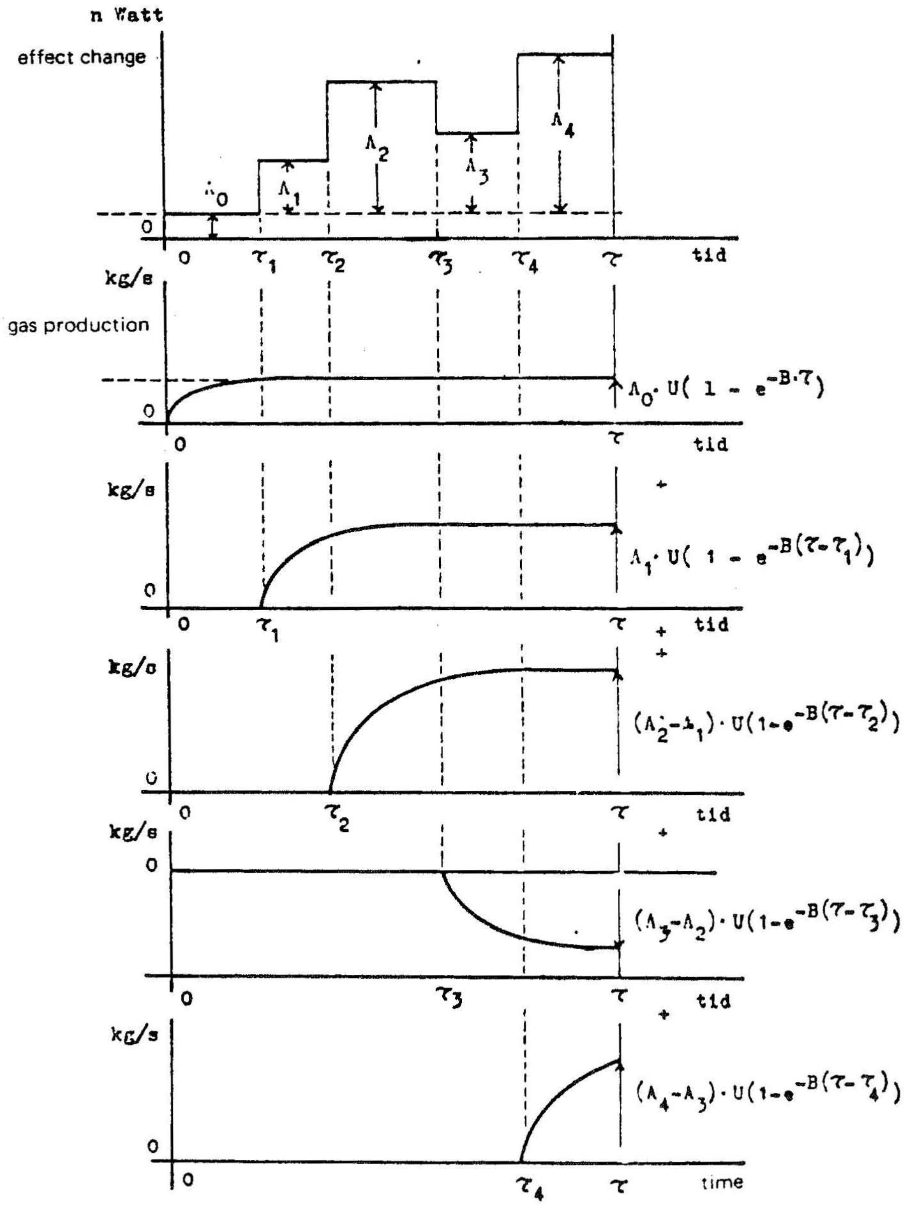

Fig. 3. Change of effect and gas production.

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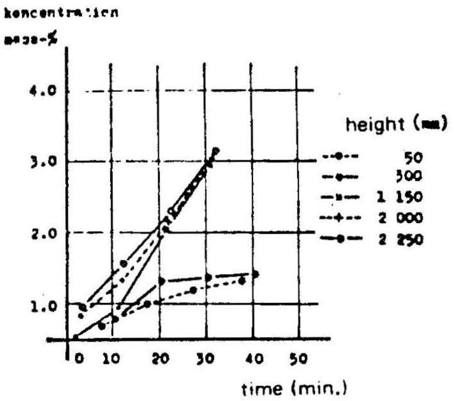

Fig. 4. Variation in concentration according to height.

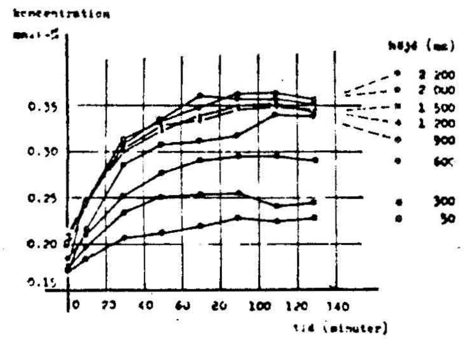

Fig. 5. Variation in concentration.

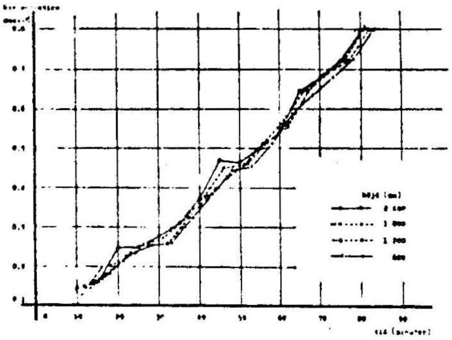

Fig. 6. Variations in concentration.

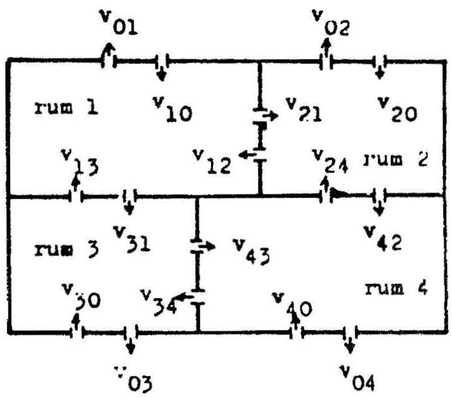

Fig. 7. Air flows in a flat.

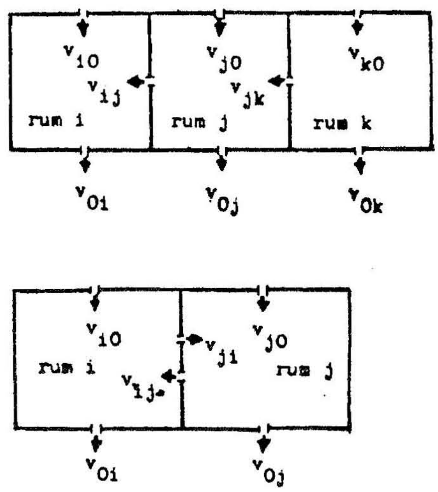

Fig. 8. Air flows in room combinations.