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Paper 29

PERFORMANCE ASSESSMENT OF A HUMIDITY CONTROLLED VENTILATION SYSTEM

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SYNOPSIS

Demand controlled ventilation systems have recently become an interesting opportunity to achieve acceptable indoor air quality while minimizing energy consumption. Although they are usually designed for buildings showing relevant variations of occupancy (e g, office buildings, schools, etc.), there are now examples of applications also in residential buildings. One example is the passive humidity-controlled ventilation system recently developed in France. This type of installation has been tested in a five- storey apartment building located in Torino, Italy, during the winter 1989. Preliminary results, concerning air temperature and relative humidity data and system operation, are presented in this paper. Analysis of data shows that the system is capable of maintaining air humidity levels below the limit values in most situations, reacting effectively to changes in the occupancy patterns and activities. The energy savings compared to a conventional constant flow ventilation system have also been calculated.

LIST OF SYMBOLS

c_p = specific heat of air at constant pressure (J/kgK)
m = air mass flow rate (kg/s)
m_v = moisture production rate (kg/s) or (g/h)
n = number of airchanges per hour (h^{-1})
p_s = saturation pressure of water at temperature T (Pa)
p_t = total atmospheric pressure (Pa)
Q_v = ventilation heat load per unit volume (W/m^3)
RH = air relative humidity (%)
T = air temperature (°C)
T_d = dew point temperature of indoor air (°C)
T_s = surface temperature of window frame (°C)
x = air humidity ratio (kg/kg)
v = specific volume of air (m^3/kg)
V = room volume (m^3)

Subscripts

i = indoor
o = outdoor
1 = ambient no. 1
2 = ambient no. 2

1. INTRODUCTION

Mechanical ventilation is seldom adopted in residential buildings in Italy. However, the synergic effect of recently developed factors (e g, supertight windows, lower indoor temperatures, and cold bridges frequently caused by incorrectly placed thermal insulation) are now often creating condensation problems, particularly in Northern Italy, where cold and rather humid winters are common. As a consequence, mechanical ventilation is now been considered as a useful technique to avoid condensation. Among ventilation techniques, novel technologies such as Humidity Controlled Ventilation (HCV) systems (i.e. demand controlled ventilation, based on humidity control) appear particularly interesting.

A multifamily building, equipped with a passive humidity controlled mechanical ventilation system, has been instrumented in order to assess the performance of this type of installation under field conditions in the climate of Torino (northwestern Italy). The building -- which is five storeys high with two flats at each level -- is a good example of current practice in the residential sector, in terms of size, construction technology, and type of heating system.

The specific aims of the investigation were:

- to check the resulting air humidity levels in terms of preservation of the building constructive elements and thermal comfort of the occupants;
- to determine if the air change rates resulting from the adoption of this ventilation strategy are sufficient to provide an acceptable indoor air quality (IAQ);
- to compare the adopted ventilation strategy with natural ventilation and traditional (i.e., without feedback) mechanical ventilation systems on the grounds of energy savings and IAQ;
- to verify the subjective reactions of the occupants to the adoption of an unconventional ventilation system.

The measurement campaign started on October 20, 1989 and ended two months later; although the extension of this campaign was rather limited, a significant range of winter climatic conditions was covered, thanks to the unusually cold weather that occurred in early December. Temperature and humidity profiles were recorded continuously outdoors and in nine representative rooms of three of the ten flats. Questionnaires were also employed to collect information about the occupants' behaviour.

2. THE SITE AND OBJECT OF INVESTIGATION

The climate of Torino can be concisely defined through the following data:

- length of the heating season: 180 days, typically from October 15 to April 15;
- number of degree-days: 2700, base 20°C;
- wind speed: usually very low during the coldest months ($\leq$1.0 m/s), scarcely exceeding 1.0 m/s during the central hours (from 12:00 to 16:00) of the day in the other months of the heating season;
- relative humidity: generally high (above 70%) from November to February.

A plot of temperature vs. humidity ratio for the typical months in the heating season is shown in Fig. 1.

The investigated building is part of a group of three buildings which can be considered identical under any point of view. Each building accomodates eleven flats (two at each floor plus a small "conciergerie" at the ground floor), has an overall volume of 3500 m^3, and a heated area of about 1400 m^2. Each flat is equipped with an individual hydronic heating system, including a gas boiler and hot water radiators.

The ventilation system is centralized, with one extraction fan in each building having a nominal power of 0.55 kW and a nominal flow rate of 3,000-4,000 m^3/h with a pressure head of 150-200 Pa. Air is evacuated from each flat through three extraction grilles, located in the two bathrooms and in the kitchen. Exhaust air from each flat is driven through two vertical ducts (I.D. = 125 mm) into the attic, and then collected by a horizontal duct (I.D. = 250 mm) to the fan. Silencing devices are located at each extraction grille and at the top of each column. Fresh outdoor air is introduced into the flats through the hygro-controlled immission grilles located in the roller blind boxes of the living room and the bedrooms. Ambient air is exctracted through hygro-controlled exctraction grilles installed in bathrooms and kitchen.

3. THE PASSIVE HUMIDITY CONTROLLED VENTILATION (HCV) SYSTEM

The passive HCV system, as well as the entire ventilation system, is manufactured by the French company ALDES. The system is based on a very simple principle: the relative humidity level indoors is controlled by means of a sensor, which is itself an actuator, i.e. a device regulating the inlet area of the air immission grilles. This concept is interesting because one device only replaces all the electromechanic chain from the transducer to the controller and finally to the actuator, with a lower investment cost and lower risks of failure.

The inlet and outlet grilles are made of PVC, as most other components of the system. The size of the grille opening varies with relative humidity, due to a humidity sensitive tissue which varies its length with relative humidity (RH). The tissue is made of a polyammidic fibre, treated and stabilized by the producer. The grille opening characteristic shows a linear variation between RH = 40 % (A = 5 cm^2) and RH = 75 % (A = 30 cm^2). In the exctraction grille the airflow rate is controlled by a rubber membrane which modifies the cross section of the air passage according to ambient air humidity.

3.1. Theoretical evaluation of HCV systems

HCV systems show an interesting capability of automatically controlling the ventilation heat load. This may be explained as follows: as the outdoor air temperature diminishes, air humidity ratio usually tends to decrease, even with increasing relative humidities (see Fig. 2). Therefore, provided the indoor conditions (air temperature, and moisture production) do not change, the amount of outdoor air required to maintain the RH setpoint will decrease with diminishing air temperature (see Fig. 3). As a consequence, ventilation losses will not increase linearly with decreasing temperature, but will keep stable within a large range of temperatures and will even decrease with decreasing outdoor temperatures (see Fig. 4).

There is an obvious theoretical limit to the possibility of controlling indoor humidity in this way: when moisture content outdoors is greater or equal than the required humidity ratio indoors no rate of air change will be sufficient. Usually, as can be seen from Figures 1 and 2, this is not the case for the heating season in Torino. However, there may be a risk of this kind during the remaining months of the year. For example, if the indoor conditions are $T_i = 20°C$ and $RH_i = 50\%$ (i.e., $x_i = 0.0073$ kg/kg), the limit values of outdoor RH above which HCV will not work are given in Table I.

Table I - Limit outdoor RH values for HCV Systems

T_o (°C)	≤9.1	10.0	12.0	14.0	16.0	18.0	20.0
RH_o (%)	100	93	82	72	65	55	50

The analytical explanation of the phenomenon for a "perfect" HCV system is given in the following. The mass flow rate of outdoor air required to maintain a constant RH indoors is given by:

$$m = \frac{m_v}{x_i - x_o} \qquad (1)$$

where

m = outdoor air mass flow rate (kg/s)
m_v = moisture production rate (kg/s)
x_i = indoor air humidity ratio (kg/kg)
x_o = outdoor air humidity ratio (kg/kg)

Eq. 1 can be rewritten in terms of airchanges:

$$n = \frac{3600 m_v}{(V/v)(x_i - x_o)} \qquad (1')$$

where

n = number of airchanges per hour (h^{-1})
V = room volume (m^3)
v = air specific volume (m^3/kg)

In the expressions above, it may be assumed that m_v and x_i are both constant. Under such circumstance, m (or n) will be a function of x_o only. This, in its turn, will be a function of outdoor temperature T_o and relative humidity RH_o through the well known relationship:

$$x_o = 0.622 \frac{RH_o p_s(T_o)}{p_t - RH_o p_s(T_o)} \qquad (2)$$

where

$p_s(T)$ = water saturation pressure at temperature T

p_t = total atmospheric pressure

Since the ventilation heat load per unit volume (W/m^3) is given by:

$$Q_v = mc_p(T_i - T_e)/V \qquad (3)$$

one finally obtains:

$$Q_v = \frac{mc_p(T_i - T_o)/V}{x_i - 0.622 \dfrac{RH_o p_s(T_o)}{p_t - RH_o\, p_s(T_o)}} \qquad (4)$$

Equations (1') through (4) were solved assuming

T_i = 20°C

RH_i = 50 % (from which x_i = 0.0073 kg/kg)

m_v/V = 10 $g/(hm^3)$.

Results of the analysis are shown in Figures 2, 3 and 4.

4. RESULTS OF THE MEASUREMENT CAMPAIGN

4.1 Indoor Air Quality considerations

The first aim of the investigation was to verify the system capability of maintaining relative humidity below a certain level. Figures 5 and 6 show respectively the frequency distribution and the cumulated frequency distribution plots of indoor RH (relative to about two months of hourly data) in the different rooms of Flat # 1 (kitchen, bathroom, living room, and bedroom). From these pictures it can be seen that, although the highest vapour production occurs in the kitchen and the bathroom, in these two rooms only 10 % of RH values are above 50%, and around 2-3% values are above 55%. The lowest RH values have been detected in the living room, and the highest ones in the bedrooms.

By means of questionnaires it was possible to define the typical daily and weekly activity schedules of the tenants in the instrumented flats, and from these the water vapour production was estimated. The questionnaires included questions about the location of the vapour producing electrical equipment, the cooking habits, the use of sanitary hot water, the presence of plants in the rooms, the daily schedules of the tenants, etc.

This also allowed to interpret the time plots of RH and estimated water vapour production. As an example, Fig. 7 shows the situation in a kitchen for a typical day: the plot indicates that the system was fully able to offset the increase in water vapour production even during cooking times.

4.2 Surface condensation problems

A second type of analysis refers to surface condensation problems and, in particular, to the condensation events on the aluminum frame of the windows, which is usually the coldest internal surface of the envelope. (Such events were indeed the most frequent problem that was pointed out by the occupants in the questionnaires.)

The analysis consists of three steps:

- determination of the indoor frame surface temperature (T_s) as a function of outdoor and indoor temperature, using a numerical heat transfer code;
- determination of dew point temperature (T_d) as a function of indoor air temperature and relative humidity;
- construction of frequency distribution plots for (T_s - T_d).

Results for the kitchen of Flat # 1 are given in Figures 8 and 9; the two bar graphs respectively show the absolute frequency of condensation events as a function of outdoor temperature and time of the day. From these data, it can be argued that it is no longer possible to control indoor humidity through ventilation in order to avoid surface condensation when two concurrent factors are present, i.e. a high vapour production rate (preparation of meals: see Fig. 9) and high outdoor humidity (which is typical of mild weather, with air temperature well above the winter minima: see Fig. 8).

4.3 Flow rate and energy savings evaluations

The evaluation of energy savings requires the determination of i) the actual number of air changes, and ii) the theoretical number of air changes required by a "perfect" HCV system to keep the indoor RH constant.

As an example, the problem was solved for Flat # 1 (which is the smallest of the three flats that were instrumented). The flat was divided into two zones: a night-zone including bedroom and bathroom, and a day-zone including living room and kitchen. Assuming that air flows between zones are zero, the problem can be solved for each zone independently. Knowing the measured values of air humidity ratio in the two rooms and outdoors, and the estimated values of water vapour productions in the two rooms, the air flows from outdoors to each room and between the rooms can be determined. For instance, for the night-zone (bedroom 1 + bathroom 2), reminding that the extraction grille is located in room 2, the following system of mass balance equations can be written:

$$\begin{aligned} x_o m_{o1} - x_1 m_{12} &= - m_{v1} + (V_1/v)(dx_1/dt) \\ x_o m_{o2} + x_1 m_{12} - x_2 m_{2o} &= - m_{v2} + (V_2/v)(dx_2/dt) \end{aligned} \qquad (5)$$

where

m_{o1} = m_{12} (air flow in and out of room 1)
and
m_{2o} = $m_{12} + m_{o2}$ (air flow extracted from room 2)

are the two unknowns.
The system of equations (5) was solved as an example for a ten hours period, and the results were compared with the theoretical air flow rate needed by a "perfect" HCV system to maintain 50% RH in the two rooms. Results in terms of total extracted air flow (m_{2o}) for the actual case and the perfect system case are presented in Fig. 10. Although the trend is qualitatively the same there is a large difference between the two values, which can be explained by the fact that the actual RH in the two rooms was well below 50%. Figures 11 and 12 show the disaggregation of flow rates (i.e., m_{2o}, m_{12}, and m_{o2}) for the actual case and the perfect case respectively. The average flow rates during the considered period for the two cases are reported in Table II.

Table II - Average flow rates and ach for actual/perfect cases.

Flows: Total				From outd. to room 1				From outd. to room 2			
actual		perfect		actual		perfect		actual		perfect	
m_{2o} m^3/h	n_{tot} h^{-1}	m_{2o} m^3/h	n_{tot} h^{-1}	m_{2o} m^3/h	n_1 h^{-1}	m_{2o} m^3/h	n_1 h^{-1}	m_{2o} m^3/h	n_2 h^{-1}	m_{2o} m^3/h	n_2 h^{-1}
29.8	0.50	13.3	0.22	16.3	0.35	10.8	0.23	13.5	1.00	2.5	0.19

The results show that the theoretical airchange rates necessary to maintain 50% RH are normally well below 0.5 ach, i.e., the recommended airchange rate for IAQ control in dwellings; this seems to indicate that by adopting a RH set-point slightly lower than 50%, values of ach would be achieved which are more suitable to offset the other normal pollutants such as carbon dioxide and body odours.

In other examples, which are not reported here for the sake of brevity, apparently meaningless results were found, such as negative inter-room flow rates or flow rates which are greater than the design flow rate of the extractors. The first fact may be interpreted as an inversion of flow (from room 2 to 1 instead than 1 to 2, as supposed in the equations 5). In the second case the overestimate of extracted flows may be due to the hypothesis of perfect mixing adopted in the equations (5). In effect, due to the location of the extraction grilles (e.g., right above the cooking equipment in the kitchens), there is an obvious "hood effect" which increases the ventilation efficiency requiring less air than would be necessary under perfect mixing conditions.

An evaluation of energy savings based on this limited amount of data only is probably not meaningful. However, it can be observed that, while the actual average airchange was 0.50 ach, a constant ventilation system maintaining the same maximum indoor RH would have required 0.83 ach, i.e., 66% more than the installed HCV system.

4.4 Occupants' acceptance

In order to assess the performance of this type of installation it was decided to gather information about the "subjective" acceptance of the system by the occupants. For that aim a questionnaire (see Table III) was developed and distributed to the occupants of both buildings equipped with the HCV system.

Table III - Questionnaire filled by the occupants.

1. Did you notice humidity problems in the building components?
2. Are you satisfied with indoor temperature levels?
3. Are you satisfied with indoor humidity levels?
4. Did you notice any malfunctioning of the ventilation system, such as:
   a - noise
   b - air draughts
   c - insufficient ventilation
   d - eccessive ventilation
   - other
5. Did you attempt to modify the operation of the ventilation system?
6. Did you modify your habits regarding window opening for airing?
7. Are there any modifications you would like to suggest about the installation or the use of the ventilation system ?

The results of the questionnaire are listed in Table IV. A total of 20 questionnaires were distributed to the tenants. Twelve families did not reply. Six questionnaires were returned, one of which incomplete. Two tenants refused to fill the questionnaire and declared to be globally unsatisfied with the system, without explaining their reasons (which probably indicates an "a priori" bias against any technological innovation!). In general, the tenants that answered the questionaire (probably, those who paid more attention to the operation of the system) expressed a global satisfaction, while pointing out some relatively minor problem.

The most frequent problem that was detected is the condensation of water vapour on the aluminum window frames in the bathroom; obviously, this is an intrinsic limitation of the system, which cannot detect the presence of cold spots due to thermal bridges: therefore, condensation cannot be avoided if, as in the case which has been investigated, window frames are made of a highly conductive material and exhibit thermal continuity between indoors and outdoors. A few of the tenants have expressed some annoyance, especially in the coldest days, for the cold draughts creeping into the bedrooms through the grilles during the night, and have also tried (successfully) to outdo the system by taping the inlet grilles. Other problems, such as temperature differences between rooms, cannot be attributed to the ventilation system.

On the positive side, several tenants noticed that the HCV system allowed them to reduce airing and that indoor humidity was acceptable even under "severe" (e.g., cooking time) conditions. The quality of indoor air was also evaluated satisfactory.

Table IV - Results of the questionnaire

Quest. #	YES # repl.	%	NO # repl.	%	NOTES
1	4	67	2	33	Condensation on bathroom window frames
2	4	67	2	33	Temperature differences between rooms
3	6	100	0	0	
4a	1	17	5	83	
4b	0	0	6	100	
4c	1	17	5	83	
4d	0	0	6	100	
5	1	20	4	80	Air inlet plugged due to low temperature
6	4	80	1	20	Reduced need of airing
7	0	0	5	100	

REFERENCES

ALDES, Technical documentation.

Fantozzi, C., *Sistemi di ventilazione meccanica controllata per edifici residenziali* (Controlled mechanical ventilation for residential buildings), Thesis in Mechanical Engineering, unpublished, Torino, 1990.

Raatschen, W. (Ed.), *Demand Controlled Ventilating System - State of the Art Review.* Annex 18, IEA. Swedish Council for Building Research D9:1990. Stockholm, 1990.

Fig. 1 – Humidity ratio vs. temperature

October–March typical values in Torino

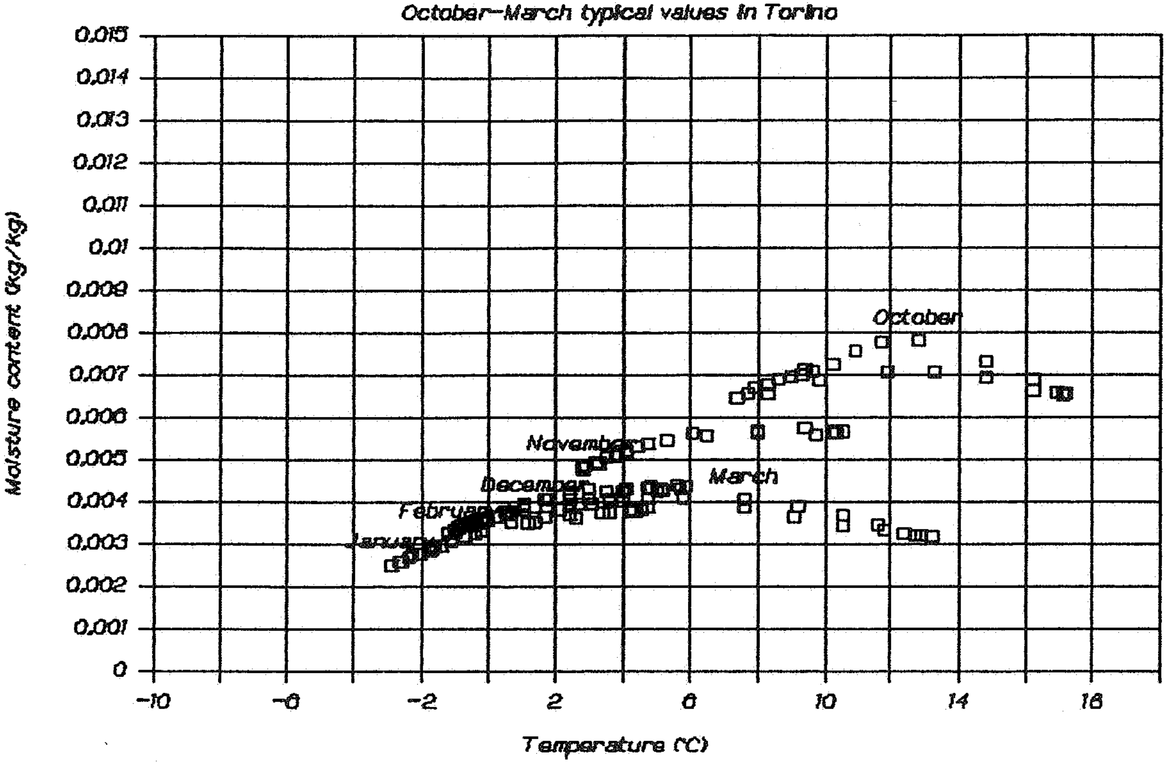


Fig. 2 – Humidity ratio vs. temperature

Parameter: relative humidity

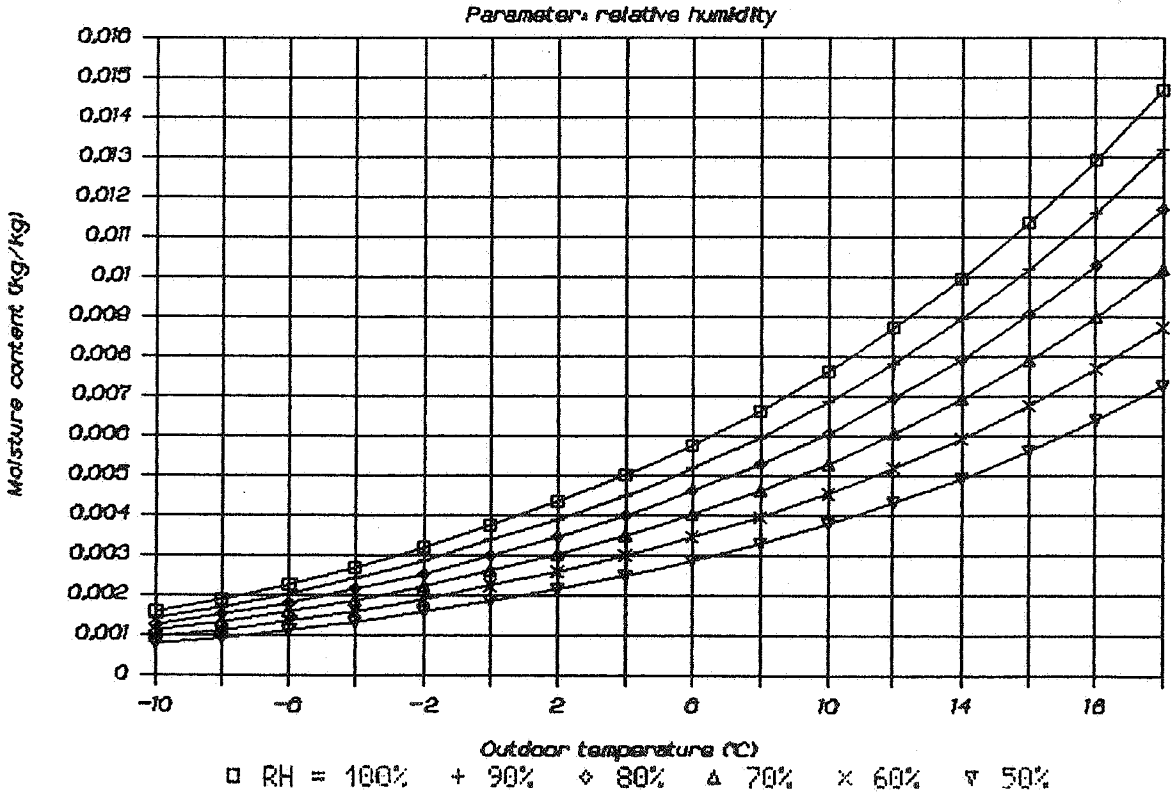


Fig. 3 – Airchanges vs. temperature

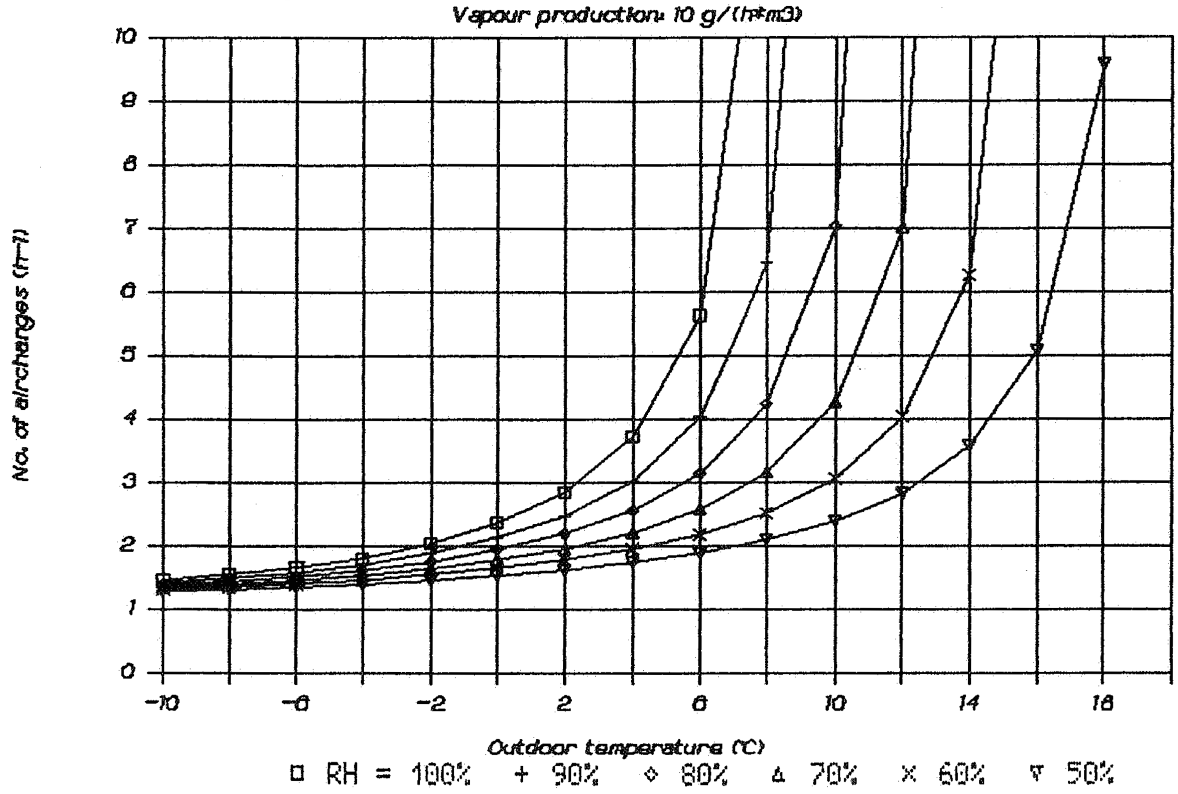


Fig. 4 – Ventilation losses vs. temp.

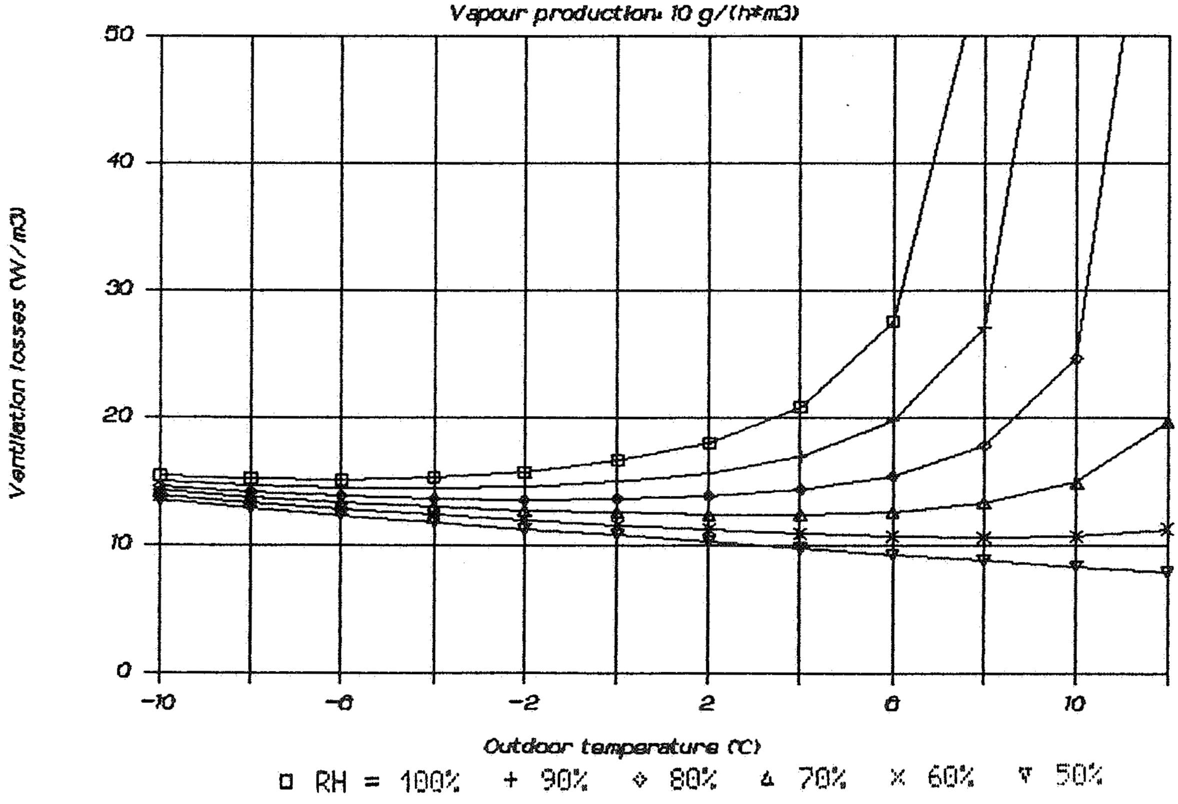


Fig. 5 - Frequency distribution of RH

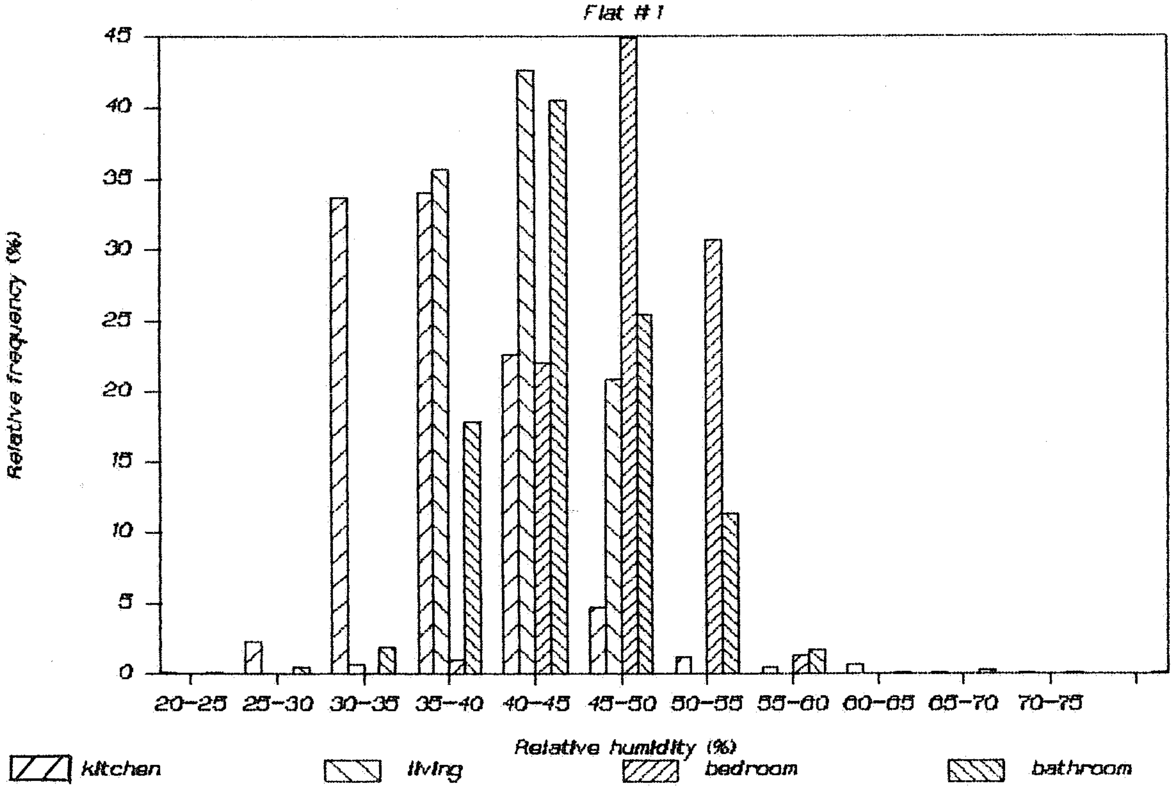


Fig. 6 - Cumulated freq . distr. of RH

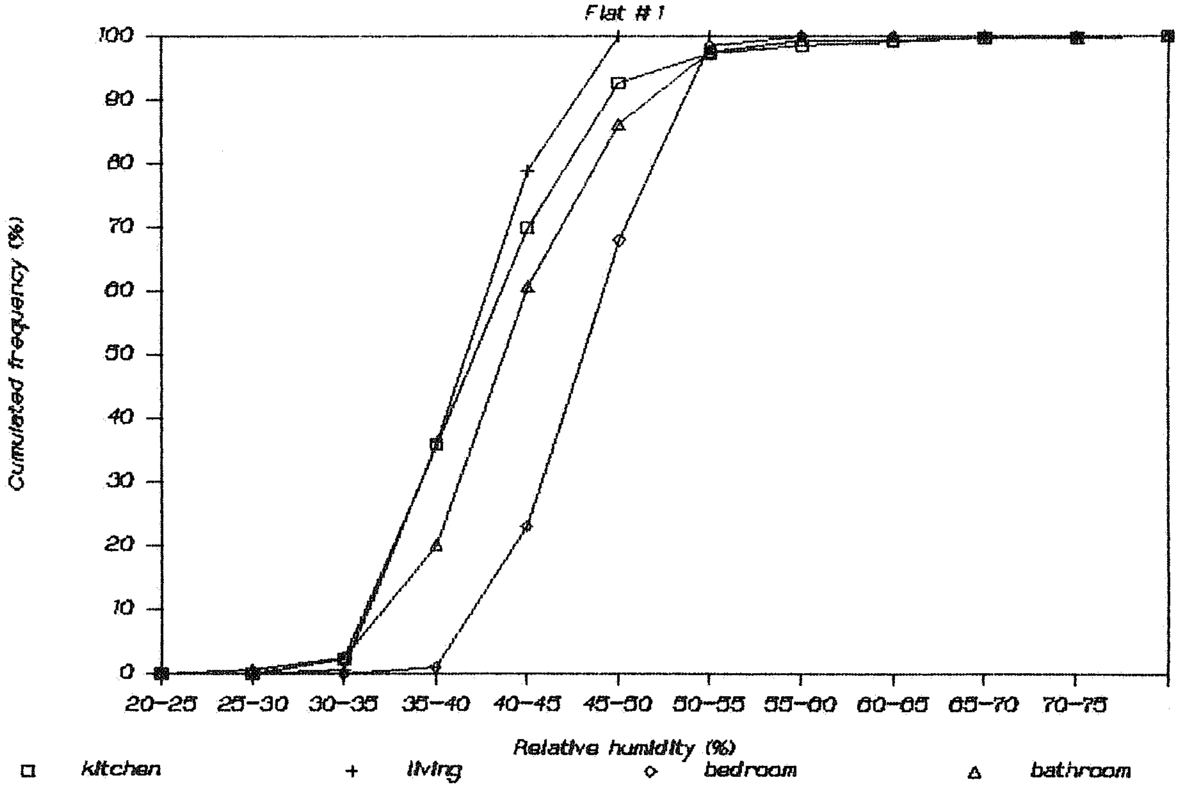


Fig. 7 – RH and Vapour production

vs. time of day

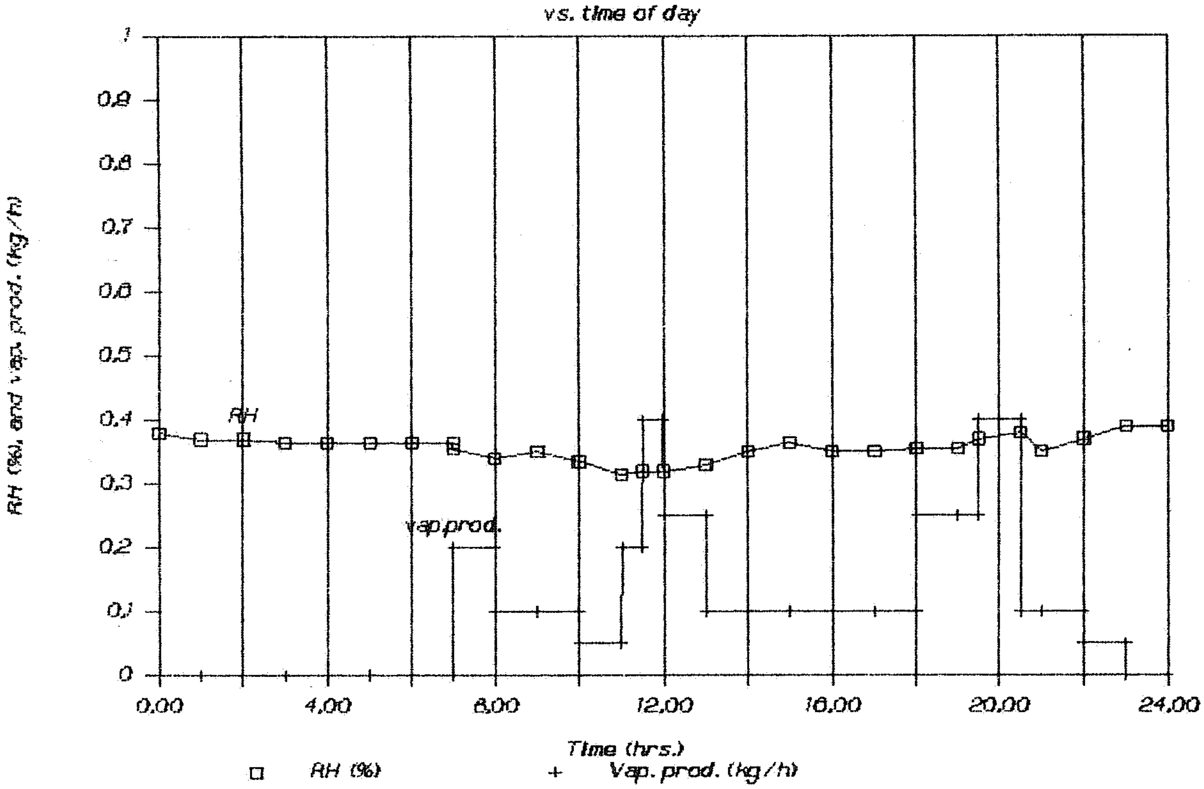
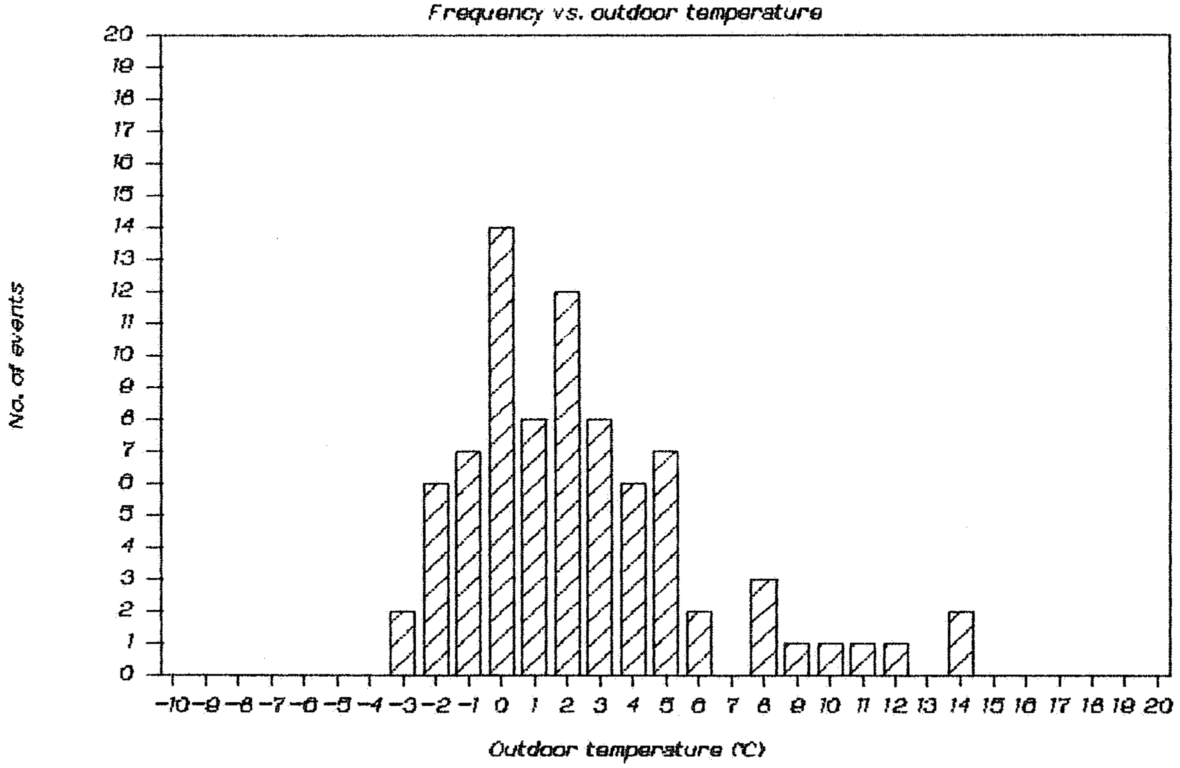


Fig.8 – Condensation events

Frequency vs. outdoor temperature



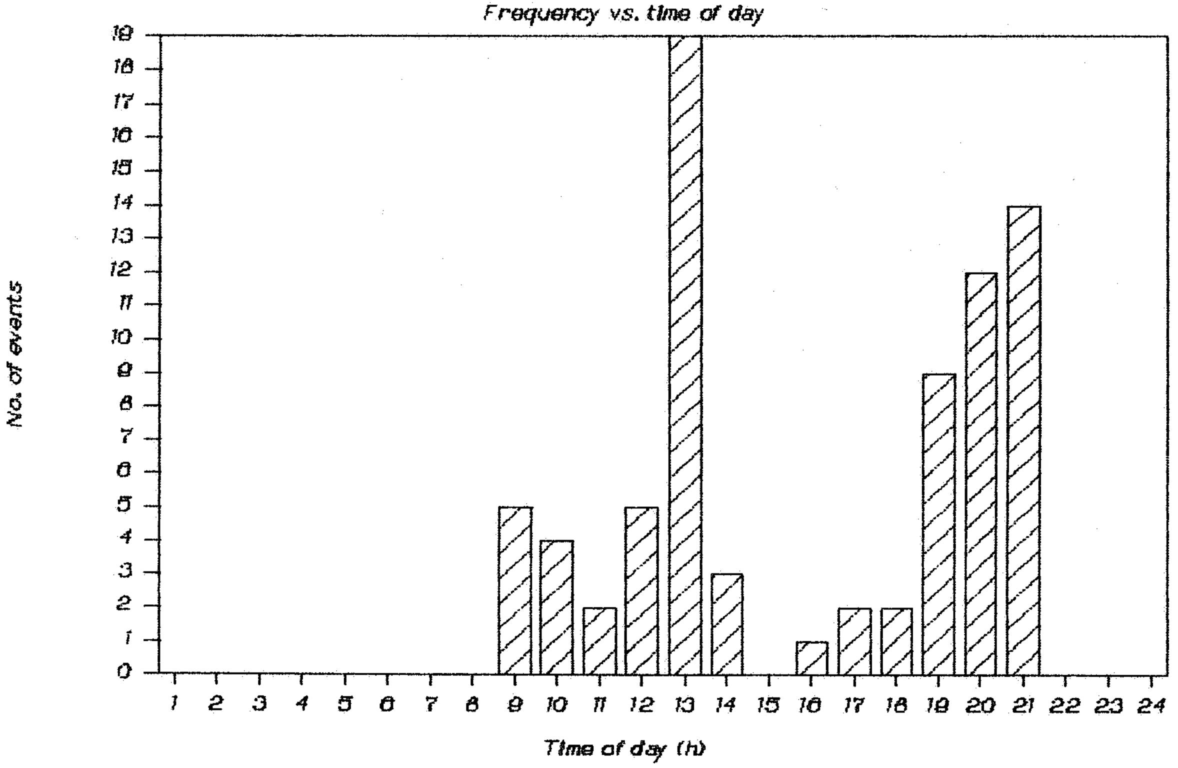


Fig.9 – Condensation events

Frequency vs. time of day

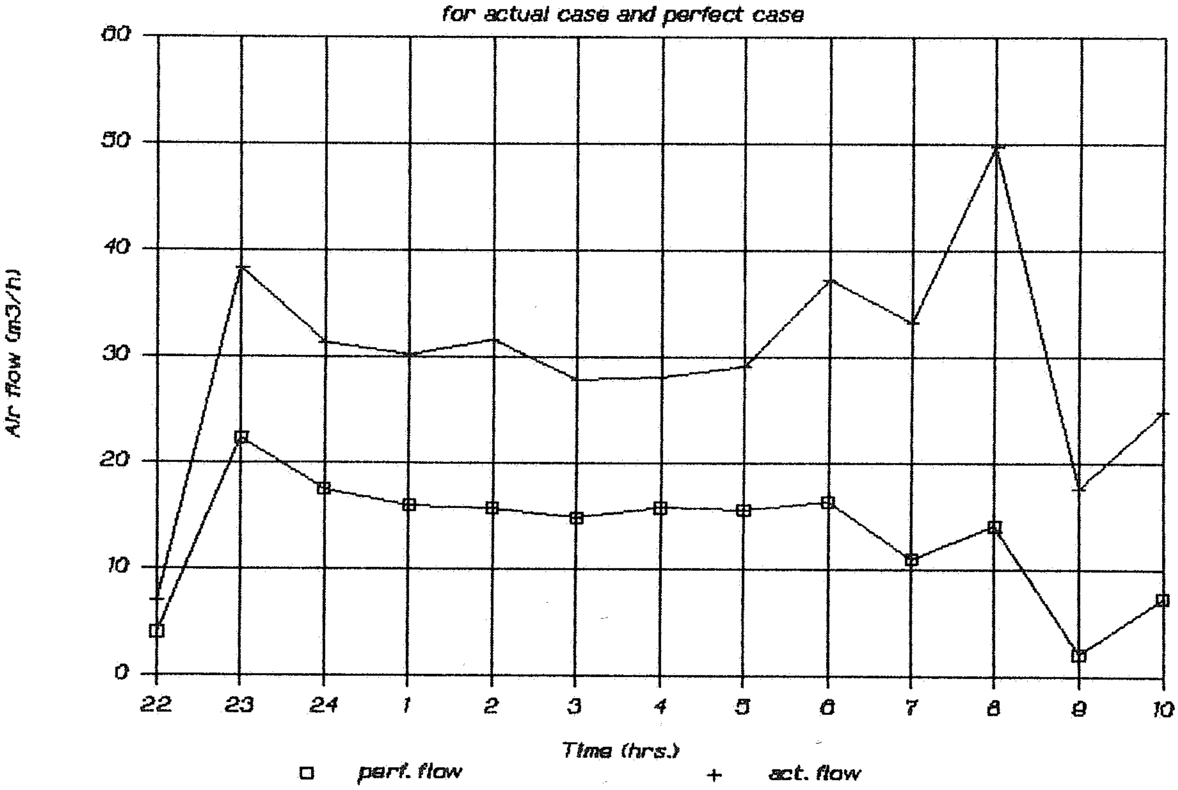


Fig. 10 – Calculated air flows

for actual case and perfect case

Fig. 11 – Calculated air flows

for actual case

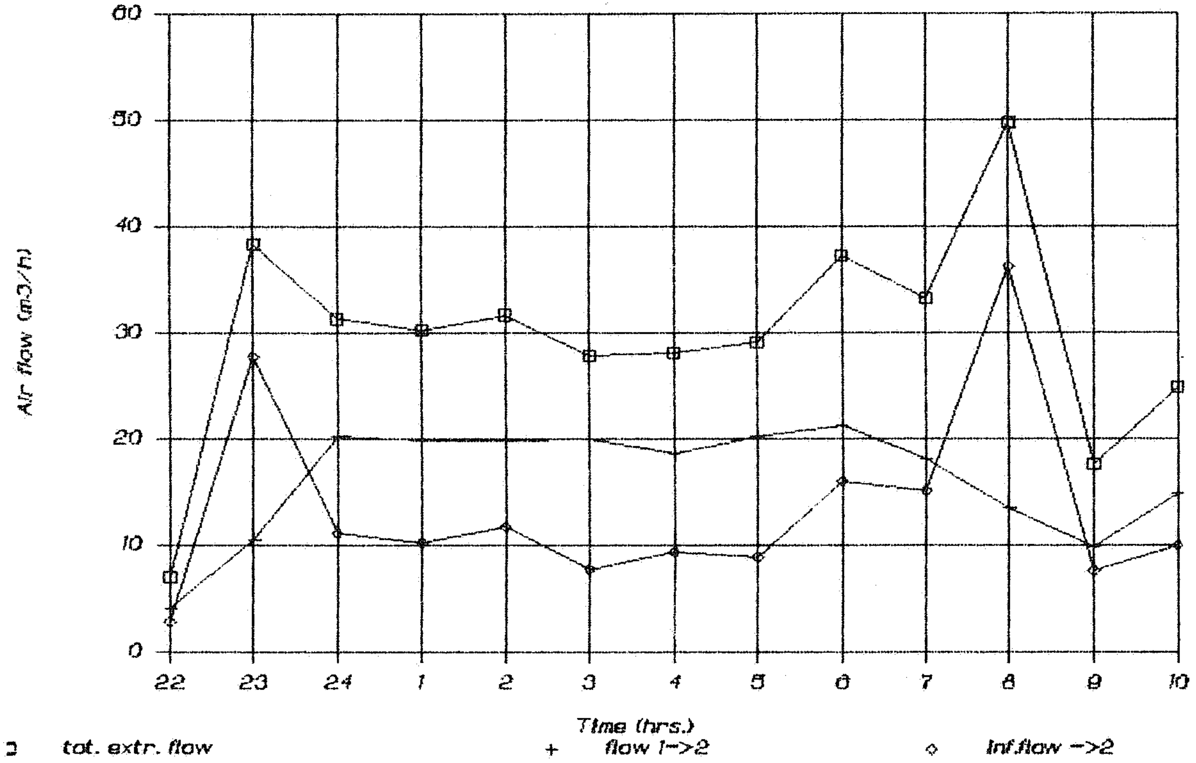
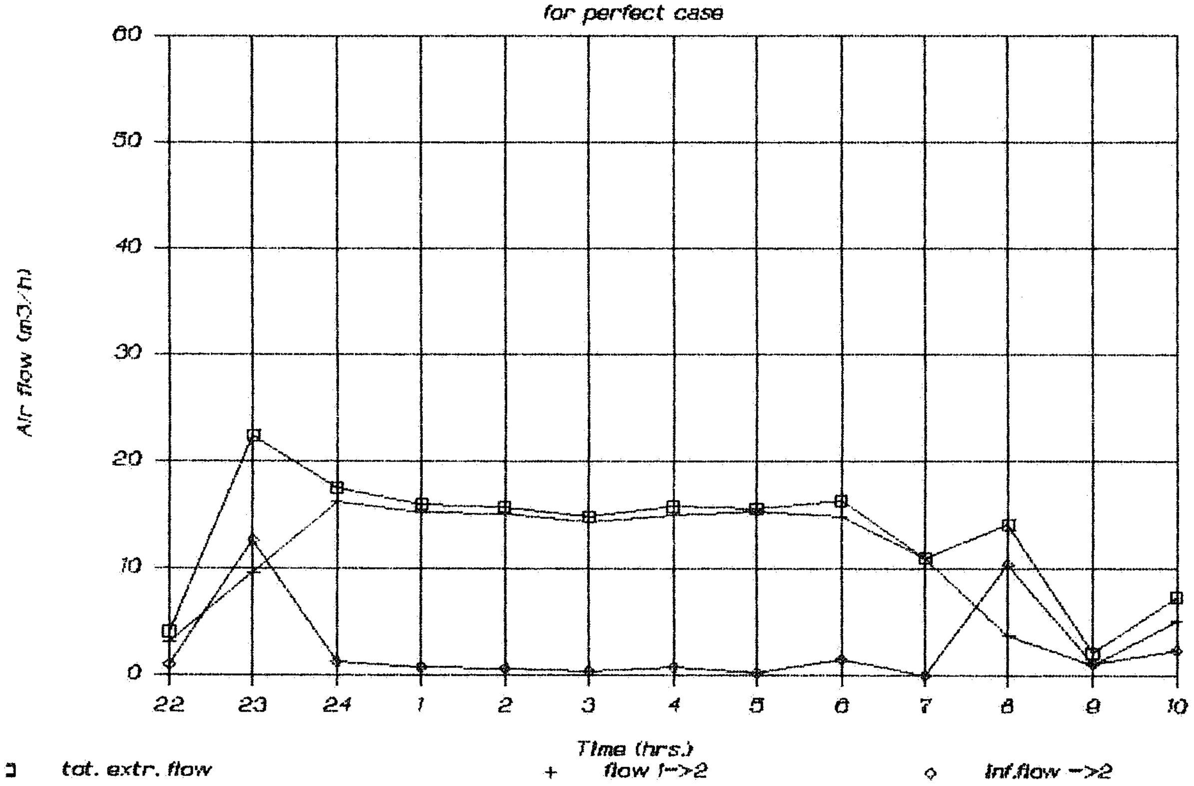


Fig. 12 – Calculated air flows

for perfect case



Discussion
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D Bienfait (CSTB, France)

Calculating the air flow rates and humidity levels as you did seems to be the proper way to assess the performance of humidity controlled systems. However, the moisture transfer in furnishings affects dramatically the RH level. Did you take that into account?

G Fracastoro (Politecnico di Torino, Italy)

No. There are other simplifying assumptions in this first approach model. The best thing will be to measure the air flows in a further stage of this study.