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A New Ventilation Strategy for Humidity Control in Dwellings - A Demonstration Project

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Synopsis

A demand controlled ventilation system with humidity as the control parameter was tested in an experimental demonstration project in 16 apartments. In the same housing complex 16 identical apartments with a constant exhaust airflow rate were included in the test as a reference group.

The purpose of the study was to investigate whether satisfactory physical health conditions could be reached in the humidity-controlled in apartments, while at the same time reducing the use of energy for heating.

In the apartments with humidity-controlled ventilation the air supply was regulated so that the humidity in the indoor air in all rooms was kept at a level which was below the limit for the growth of house dust mites and just sufficient to prevent condensation on all indoor surfaces of the building. The airflow could increase up to a maximum to the requirements as stated in the Nordic Committee on Building Regulations and in the Danish Building Code. The airflow in the reference apartments was at a constant level, according to the requirements.

In the humidity-controlled apartments the total outdoor air change, the mechanical exhaust airflow rate, and the energy consumption for heating were significantly reduced compared to the reference apartments, at mean temperatures per day below 9°C and at the same time the humidity criteria were met.

In addition to the technical study, a resident indoor climate satisfaction study was carried out in the housing complex. The main purpose of this study was to gain knowledge of the residents' appraisals of the indoor climate.

1. Introduction

A high concentration of humidity in the indoor air of apartments provides suitable growing conditions for house dust mites and mould. Both house dust mites and mould cause allergies in human beings. In addition, rot and mould seriously damage the building construction. The criteria in building codes and ventilation standards for mechanical ventilation of apartments have the primary aim of ensuring the exhaust of humidity from the indoor air, and thus avoid the disadvantages of excessive humidity concentrations. The use of mechanical ventilation guarantees a minimum level of ventilation in dwellings. However, if the ventilation has a constant air volume, regardless of the ventilation needed, the outdoor air exchange and the use of energy for heating may in certain periods be unnecessarily high. Therefore, it is obvious to attempt to regulate the ventilation rate by humidity and only ventilate *where* and *when* humidity occurs. This condition can be established through a ventilation system that has individual control of air volumes for each room of a dwelling. For instance, humidity can be kept at a level which is just sufficient to prevent condensation on indoor surfaces of the building and below 45 % of relative humidity which is the limit necessary to reduce the growth of house dust mites [1,2].

2. Purpose

The purpose of the present study was to investigate if satisfactory physical health conditions could be obtained in apartments with humidity-controlled ventilation while at the same time reducing the use of energy for heating.

In this context, satisfactory health conditions means humidity conditions that can reduce the occurrence of house dust mites and fungus spores and prevent condensation on indoor surfaces of the building.

3. Method

3.1. Material

3.1.1 The apartments and the ventilation system

Two groups of 16 identical apartments were provided with mechanical ventilation systems. In group one, a humidity-controlled ventilation system was installed where the ventilation in each room of the apartments was regulated by the humidity level of the indoor air. In group two (the 16 reference apartments), the ventilation system comprised of a constant mechanical exhaust with an airflow rate according to the building code [2,3]. Each group of apartments was ventilated by two exhaust fans. In the investigation period some occupants moved from their apartment and others would not participate in the investigation. Therefore only 13 apartments having each type of ventilation system were used in the investigation. While originally identical in pairs of two, the size of the remaining 26 test apartments now varied slightly. The average net floor area in the humidity-controlled apartments and in the reference apartments was respectively 49 m^2 and 55 m^2, and the average number of inhabitants per apartment was respectively 1.7 inhabitants and 1.4 inhabitants.

Connected to the living room of the apartments there was an enclosed veranda with an external wall constructed with two layers of glass. Glass doors separated the veranda from the living room.

In both types of apartments, the indoor air was exhausted from the kitchen and the bathroom and the outdoor air was supplied through a fresh air valve in each room. In the kitchen there was a manually controlled cooker hood which was connected to the ventilation system. In the humidity-controlled apartments, each fresh outdoor air valve was controlled by a humidity sensor, except for some of the apartments where the fresh air valve in the living room was manually controlled as in the rooms in the reference group. Here, the manual fresh air valve was designed as a slide valve in the window frame. A ground-plan of an apartment with the positions of the fresh air valves and corresponding humidity sensors and the mechanical exhausts is shown in figure 1.

The humidity sensors were constructed as capillary hygrostats.

3.1.2 Principle of regulation

At outdoor air temperatures greater than 1°C, the relative humidity in all bedrooms was regulated up to a maximum of 40 % and in all other rooms up to a maximum of 45 %. When a humidity sensor registered higher relative humidity than the set point, the on-off regulated fresh air valve in the same room was opened, and again closed when the relative humidity had decreased to a value of approximately 5 % relative humidity below the set point. In the kitchen and the bathroom the exhaust airflow rate was regulated

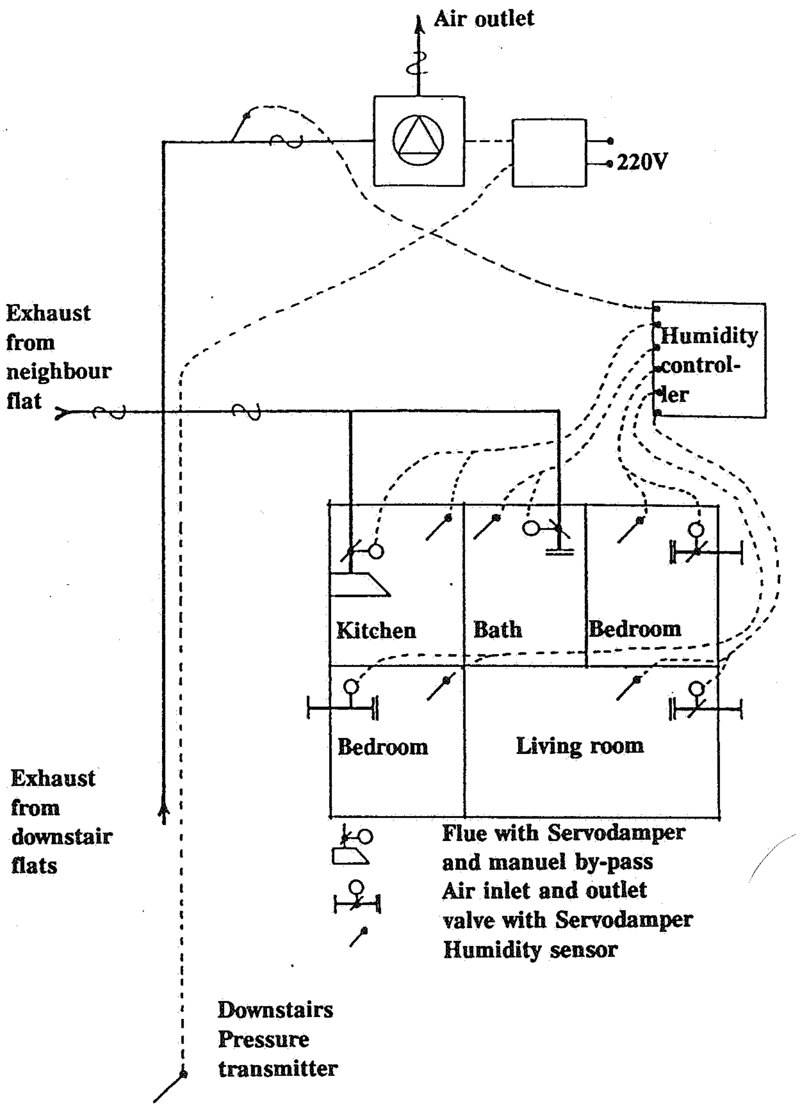

Fig. 1. The position of the fresh air valves and the humidity sensors in an apartment.

automatically by a motor driven exhaust air valve. The airflow rate of the fan was automatically controlled relative to the ventilation need by the difference between the pressure in the apartments and the pressure in the fan inlet. The minimum exhausted airflow rates for apartments with respectively small (< 7 m^2) and big (> 7 m^2) kitchens were respectively 14 l/s and 20 l/s. When dehumidification was needed both in the kitchen and the bathroom, the airflow rates could rise to the requirements in the building code [2,3], respectively 30 l/s and 35 l/s. The opening of fresh air valves in the other rooms did not change the total exhausted air volume but secured the supply of outdoor air to the these rooms.

At outdoor air temperatures less than 1°C, a criterion to prevent condensation on window panes was added to the control criteria of humidity limits of 40% and 45% relative humidity. The limit of occurrence of condensation was determined by the relation between the relative humidity in the indoor air (RH_i) and the outdoor temperature (t_u) by the model:

$$RH_i < EXP(0.0360 * t_u + 3.85) - 3 \quad (\%)$$

The exponential term of the model expresses the limit for the indoor relative humidity when condensation occurs, based on a calculation of the heat transmission of a 1 meter high thermo window with two layers of glass. The heat radiation and the convection have been calculated individually and apply to the average glass surface. To simplify the regulation system, the relative humidity was registered in a main exhaust duct that covered eight apartments. The value, -3, in the model should partly compensate for this simplification. When the relative humidity in the main duct was higher than the one calculated by the model, all fresh air valves opened and the exhausted flow rate from all eight apartments was increased to the requirement in the building code. If the indoor relative humidity then decreased to 5 % below the value calculated by the model, the hygrostats regulated the fan's performance and the air valve positions to the level adjusted at the hygrostats.

The limits for the relative humidity that regulate the valve and the fan are shown in figure 2.

When forced ventilation was needed in the kitchen, it was possible to increase the airflow rate manually up to approximately 50 l/s by means of opening a valve in the cooker hood. In the bathroom, the exhaust air flow rate could be increased (by turning on the light switch) to 15 l/s, which is the requirement in the building code [2,3].

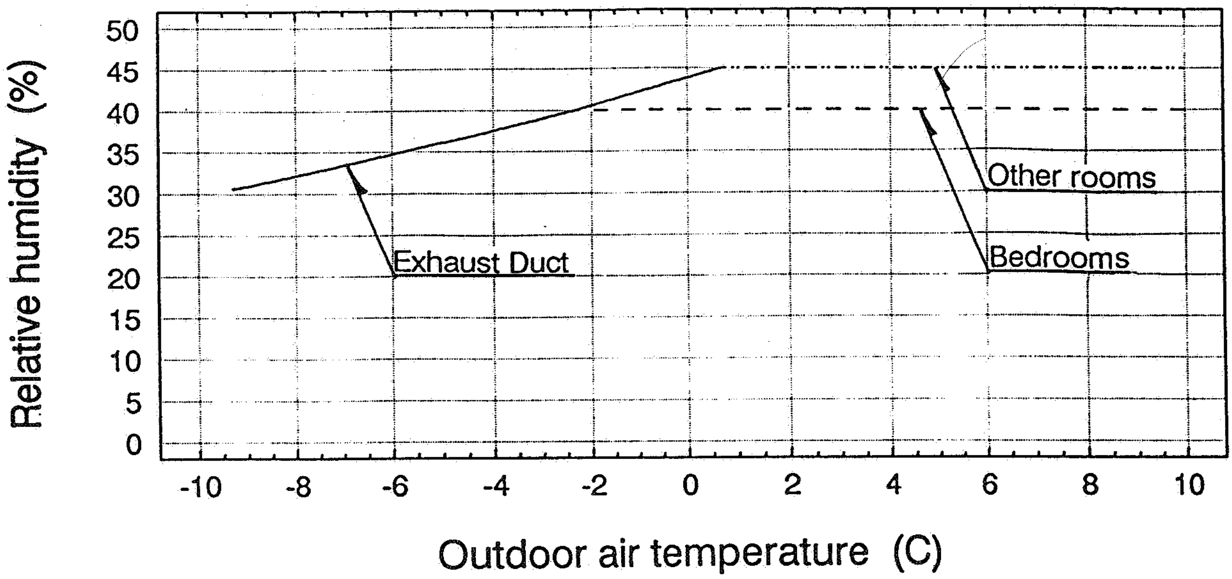

Fig. 2. The limits for the relative humidity that control the regulation of the valves and the fan. The upper value at the dead band of the hygrostats at 5 % relative humidity was adjusted at the drawn limits at 40 % and 45 %. The registered relative humidity in the exhaust duct is the mean value from eight apartments.

3.2 Investigation

3.2.1 Control and registrations

Before starting the registrations, all hygrostats and humidity sensors were calibrated and all airflow rates and regulation functions were checked. The registrations were then performed during three periods.

During two weeks at a mean outdoor air temperature per day varying from -5°C to 3°C and at an average of -0.1°C and a mean relative humidity at 86 % the registrations consisted of:

- The total mean air change rate for the apartments and the air change rate for the bedroom in all apartments. Use of passive tracer gas technique.
- The mean relative humidity and the mean air temperature in the living room and the bedroom in all apartments. Use of thermohygrograph.
- A questionnaire investigation concerning the indoor activities which could influence the amount of indoor air humidity. The answers were focused on the two week registration period.

During three months at mean outdoor temperatures per day varying from -3°C to 15°C and an average of 7°C the mean total exhaust flow rate per day was registered for each apartment with humidity-controlled ventilation. Use of hot wire anemometer in each main exhaust duct.

One year after the investigation was started the hygrostat readings were checked. In the first half year the consumption of energy for heating was registered.

3.2.2 User satisfaction study

A study of users' satisfaction with the indoor climate of the apartments was included in the research design for the evaluation of the humidity-regulated ventilation system. The purpose of the user study was to investigate interaction effects between the perceptions and behaviour of users (i.e the residents in each apartment), the characteristics of the ventilation systems and the physical indoor climate characteristics.

The hypothesis was that residents in apartments with humidity-regulated ventilation would experience no significant defecit in satisfaction with the indoor climate compared with residents in apartments with constant ventilation at the normal rate.

The user study included a series of pilot interviews with 5 households and the caretaker, and a postal questionnaire survey of all residents.

The "satisfaction model" for the interviews and survey can be described as a series of inter-related but conceptually discrete "facets", some comprised of objective conditions, others subjective; each facet being made up of different "elements"[4, 5]. Using a so-called "mapping sentence" (- being a shorthand, textual presentation of a research problem), the following definition expreses how the level of user satisfaction can be conceptualized as a function of relations between 6 main facets:

Mapping sentence: *Residents' LEVEL OF SATISFACTION with indoor climate (expressed as high/low) is a function of:*
Facet (A) - her own situation ("biographical" characteristics),
(B) - her experience of physical (climate) impacts
(C) - her home-use and behaviour
(D) - her health and welfare, (and possible irritation/ill-health symptoms)
and (E) - actual physical conditions in the apartment.

Pilot Interviews were tape-recorded and analysed in relation to each of the 5 facets (above). The *questionnaire survey* was used to record 1. user behaviour which could affect the humidity of the apartment, and 2. users' observation of condensation/humidity in the apartment.

4. Results

4.1 Physical condition

The mean exhaust airflow rate per day from one apartment is plotted as a function of the mean outdoor temperature in figure 4. The mean airflow rate is estimated by three linear regression equations.

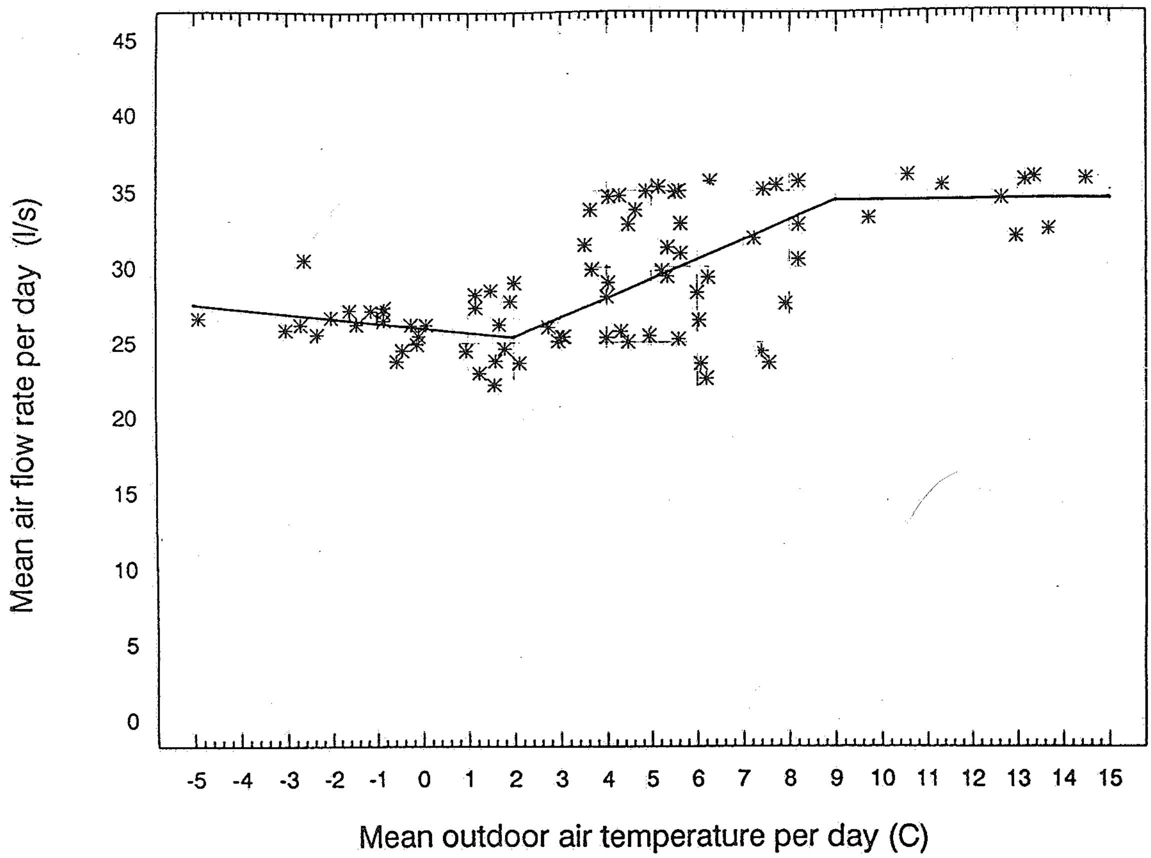

Fig. 4. Plot of the mean airflow rate per day versus the mean outdoor temperature per day.

The percentage reduction of the mean airflow rate - compared with the flow rate measured in the reference apartments - is calculated as a function of the mean air temperature per day for each apartment with humidity-controlled ventilation. The average percentage reduction for all apartments is shown in figure 5.

In the living room and the bath room for both type of apartments all registrations of the relative humidity was below 45 %. In the bedroom in the humidity-controlled ventilated apartment and in the reference apartment the variation of the relative humidity were respectively 32-43 % and 27-48 %.

On the basis of the measured room air temperatures and relative humidity the vapour pressure and the vapour content of the indoor air can be calculated. The difference between the vapour content of the indoor air in the living room and in the bedroom and the vapour content of the outdoor air is shown in figure 6.

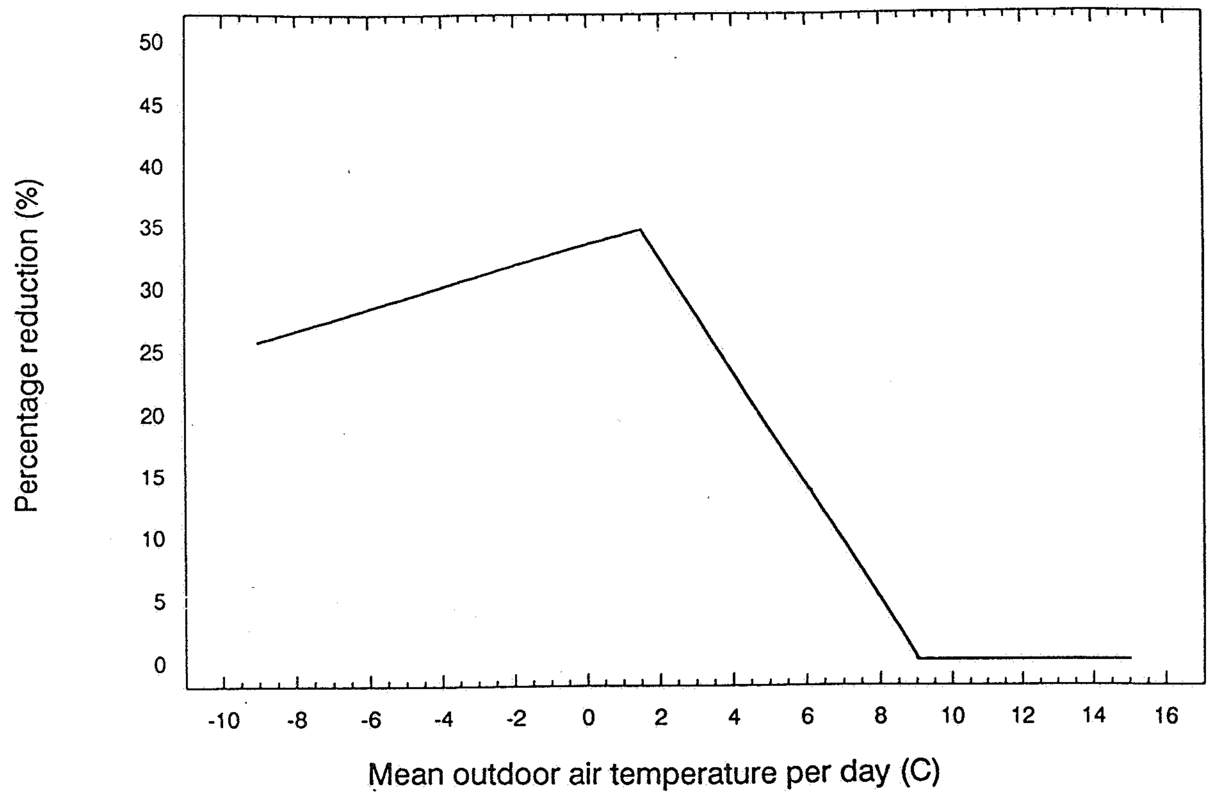

Fig. 5. The percentage average reduction in mean airflow rate.

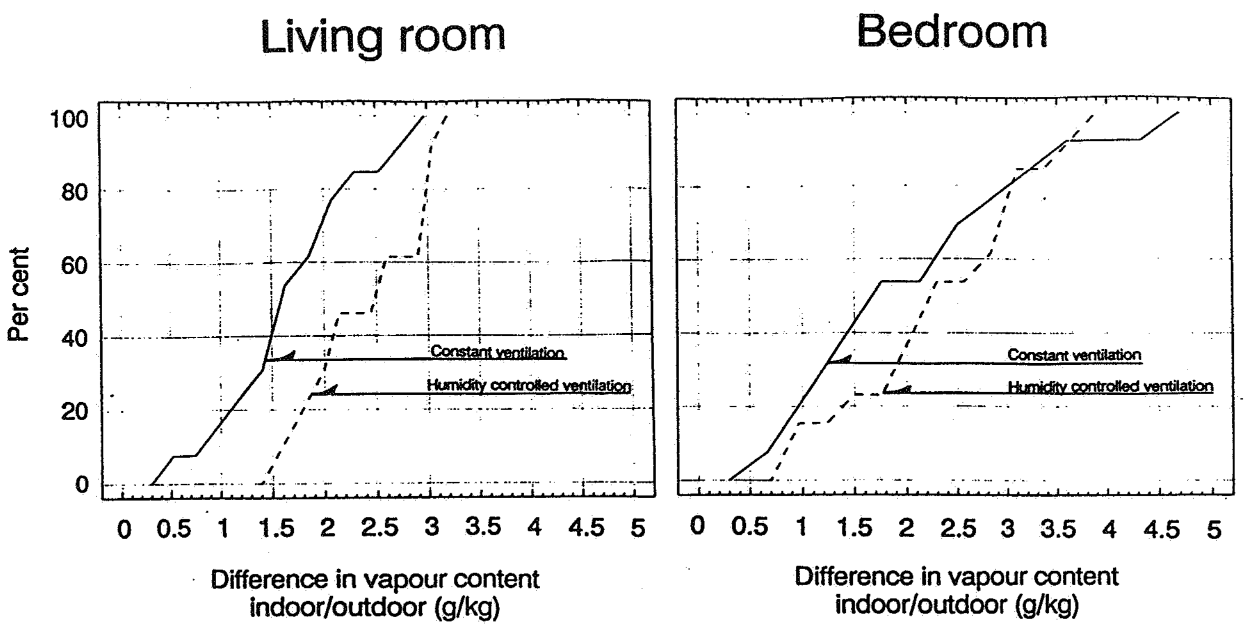

Fig. 6. Cummulative, relative fequency of the difference in vapour content in the indoor air of the living room and the bed room and in the outdoor air illustrated.

A statistical presentation of data for the first two weeks' registration is shown in table 1.

Table 1. Results of the registrations.

Parameter	Part of apartment	Humidity-controlled ventilation Mean ± [2]Std.	Constant ventilation Mean ± [2]Std.	[1)]t-test Level
Temperature	Living room	20.2 ± 2.2°C	21.0 ± 2.2 °C	
	Bedroom	20.6 ± 1.5°C	21.2 ± 1.4 °C	
Difference in vapour content indoor/outdoor	Living room	2.37 ± 0.58 g H_2O/kg air	1.66 ± 0.69 g H_2O/kg air	p=0.004
	Bedroom	2.30 ± 0.97 g H_2O/kg air	2.07 ± 1.16 g H_2O/kg air	p=0.29
	Bathroom	2.09 ± 1.54 g H_2O/kg air	1.54 ± 0.61 g H_2O/kg air	p=0.020
Relative Humidity	Living room	37.5 ± 3.1 %	32.2 ± 1.7 %	p=0.0001
	Bedroom	36.6 ± 3.7 %	35.2 ± 6.2 %	p=0.25
	Bathroom	33.0 ± 4.6 %	30.4 ± 4.1 %	p=0.06
Moisture generation rate	Whole apartment	6.25 ± 2.0 kg H_2O/day	6.69 ± 3.5 kg H_2O/day	p=0.35
	Bedroom	1.38 ± 0.46 kg H_2O/day	2.07 ± 1.4 kg H_2O/day	p=0.1
Total outdoor air change	Whole apartment	0.77 ± 0.22 h^{-1}	1.08 ± 0.34 h^{1-}	p=0.002
	Bedroom	0.63 ± 0.22 h^{-1}	1.24 ± 0.86 h^{1-}	p=0.002
Total outdoor air supply	Whole apartment	25.5 ± 6.1 l/s	39.0 ± 10 l/s	p=0.002
	Bedroom	5.64 ± 1.9 l/s	10.6 ± 7.5 l/s	p=0.003

[1] *Testing of the difference between the mean values. Where the test level p is higher than 0.05 the two mean values can be considered as equal. In all tests the standard deviations are pooled.*
[2] *Standard deviation.*

4.2 User satisfaction study

Resident characteristics

Residents who were interviewed included the following persons :

- a retired married couple, wife asthmatic (apartment with constant ventilation)
- a young, female single student, smoker (humidity-controlled ventilation)
- an elderly wheelchair user, heavy smoker and his family (humidity-controlled ventilation)
- a young mother and 2 small children (humidity-controlled ventilation)
- a young couple, no children (humidity-controlled ventilation).

Knowledge of system: Neither the residents nor the caretaker were informed in detail about the measurement principles of the humidity-controlled ventilation system. This made it impossible for the caretaker to explain to the residents precisely when and why the humidity-regulated ventilation system came into effect. Some residents felt that during periods of peak-ventilation need (food preparation in evenings), the flow was too low, as smells could come from other flats. Several residents would like to have had the possiblity to shut outside air vents completely in windy periods.

General satisfaction with apartments: Was not recorded in detail in the pilot interviews but was indicated by residents as largely positive. The apartments were regarded as very attractive and functional. West-facing apartments receive plenty of daylight. It was observed that *outdoor climate* effects are particularly strong due to the exposed sight of the housing, which faces the prevailing south-westerly wind. Strong winds, driving rain, snow, strong sunshine and heat have led to rain-water seapage around window-frames and concrete elements in some flats.

General perception of indoor climate: An interview with the housing caretaker, who received queries and complaints about the ventilation systems revealed that particular problems were related to the noise nuisance and draughts from air intake valves (vents) in the walls of apartments with humidity-regulated ventilation.

Noise and draughts: Positioning of air intake vents (in bedrooms and kitchens) was regarded as particularly irritating on cold or windy days. Due to the limited possibilities for arranging furniture, residents found that cold air fell directly onto the bed and gave draughts when sitting at the kitchen table. Noise from the ventilation system (experienced as "whistling" at the air outlet points in bathrooms and kitchens) was irritating for some residents. After the experimental period and measurements were completed, some residents have had covers fitted to the outlet valves to reduce noise, and one couple has since blocked the valve completely.

Health: One resident, who previously had an asthma condition, has used much less medicine than she did in the former dwelling (- a traditional, brick-built house with a basement). She regards the indoor climate as being conducive to her improved health. She lives in an apartment with constant mechanical ventilation.

5. Discussion

In figure 4, the three linear regression equations are divided by the mean air temperature at 2 °C and at 9°C. At a mean air temperature lower than 2°C, the criterion of avoiding condensation significantly affects the airflow rate which is increased by lower outdoor air temperatures. Since the need for dehumidification to prevent condensation grows significantly at low outdoor air temperatures, the airflow rate will also increase as shown in the figure. At mean air temperatures between 2°C and 9°C, the airflow rate increases up to around 35 l/s. At a mean air temperature per day higher than 9°C, the airflow is constant, i.e. the outdoor air does not have any dehumidification potential with respect to the indoor air.

The three regression equations are estimated for all apartments. The abscissa value for the points of discontinuity of the estimations and the high scatter of the points of the airflow rate do not differ essentially for the other apartments from what is shown in figure 4. However, the differences between the levels of the airflow rate of some apartments are more than 7 l/s at 2°C.

The high scatter of points of the mean airflow rate in figure 4 shows that the ventilation needs differ greatly in the individual apartments. The differences are due to a high variation in the moisture generation rate and in the dehumidification potential of the outdoor air in combination with irregularity of airing.

Figure 5 shows that the achieved maximum percentage reduction of the mean airflow rate as average for all apartments was around 35 % (12 l/s) at 1.5°C and the outdoor air had no dehumidification potential at a mean air temperature per day higher than 9°C. As a consequence of the lower airflow rate, a saving in energy for heating is obtained. From a mean outdoor air temperature per day between -2°C, which was the lowest temperature during the energy registration, and 6°C, the registrations of energy for heating showed a linear increase in the difference of energy consumption for the two types of apartments. At a decrease of one degree in the outdoor air, the difference in the needed heating effect was increased by 0.75 W/(m^2 net floor area), i.e. the save in energy for heating for an apartment at a net floor area at e.g. 70 m^2 and a mean outdoor temperature at 0°C is approximately 7.6 kWh per day.

The criterion for condensation for the humidity-controlled ventilation system is in operation at mean air temperatures less than 1°C. In the two weeks' registration, during which it was tested if the regulation system could prevent condensation, 70 percent of the outdoor air temperatures registered each hour was below 1°C. Also, knowing from figure 5 that the minimum mean ventilation need appeared at 1.5°C, the outdoor temperature in the test period was estimated to be low enough to perform an assessment of the criterion of condensation. At a difference in the vapour content of the indoor and outdoor air of 2.5-3.0 g H_2O/ kg air, condensation on window panes normally will not occur. At a difference of 4.0-5.0 g H_2O/ kg air, condensation problems in houses with windows with 2 layers of glass may occur when the indoor air temperature is decreased and curtains cover the windows. Figure 6 shows that in 15-20 % of the registrations, the difference in vapour content of the indoor and outdoor air in the apartments with humidity-controlled ventilation system exceeds 3.0 g H_2O/ kg air, but no values exceed 3.9 g H_2O/ kg. The scatter of the registrations for both rooms in the reference apartments in the figure is much higher, which may be due to the fact that the valve in the reference apartment was not activated as often as the automatical humidity-controlled valve. From the interviews of the occupants it appeared that the valves were almost always open or closed. Therefore, the difference in the vapour content in the indoor and the outdoor air also in some cases can be high. In one bedroom the difference was more than 4.5 g H_2O/ kg air.

The test of the difference between the mean values in table 1 shows that there was no significant difference in the moisture generation rate in the two types of apartments, both when calculated for the whole apartment ($p=0.35$) and for the bedroom alone ($p=0.10$).

In the bedroom, the relative humidity and the differences in vapour content in the indoor and outdoor air did not differ. However, the difference in the outdoor air supply rate to the room was large ($p=0.002$). These relationships strongly indicate that the removal of vapour content from the bedroom happened more effectively by the humidity-controlled ventilation system, i.e. when the vapour content increases, the ventilation airflow rate increases. Calculating the removal factor as gram removed vapour per liter supplied outdoor air per second for each apartment, the mean removal factor for the apartments with humidity-controlled ventilation was 1.4 times higher than that for the reference apartments. For the living room this factor was the same, but here the relative humidity and the vapour content in the indoor air differs significantly. The regulation of humidity in the living room is less effective, presumably due to two main reasons:

1) In the half of the apartments the living rooms had only a manually controlled fresh air valve by which a part of the outdoor air needed for dehumidification was not led through the room if the valve was closed.
2) The hygrostat in other living rooms were placed at the door leading to the corridor and the fresh air valve in the opposite wall close to the kitchen where the air was exhausted. In that way, the hygrostat often could be surrounded by air coming from the adjacent room into the corridor.

Selecting the few apartments left for which the above reasons did not apply, the average removal factor for the living room was more than three times higher for the apartments with humidity-controlled ventilation than for the reference apartments. The analysis indicates that simple fundamental physical changes would be able to improve the regulation system and probably further reduce the energy consumption for heating.

In the questionnaire, the occupants were asked if they had observed condensation on the window panes during the two week period. A few more occupants in the apartments with humidity-controlled ventilation than in the reference apartments had observed condensation. It sometimes occurred in the living room, when the occupants dried clothes in the room or took a shower in the bathroom. In the apartments with humidity-controlled ventilation, all the condensation was observed in the type of apartments with less effective humidity regulation due to a manually controlled fresh air valve, as described in reason 1) above.

When the criterion to prevent condensation controlled the ventilation, one humidity sensor in the main exhaust duct functioned as reference sensor for eight apartments. If one sensor was used in the main exhaust duct from each apartment, the regulation probably would be substantially improved.

The check of the hygrostat readings one year after they had been calibrated showed that the hygrostats should be recalibrated at least once a year, e.g. just at the time when the mean outdoor temperature per day is decreasing below 9°C.

The mean total outdoor air supply in the two weeks' registration period was 28 % less than the requirement in the building codes [2,3]. However, the vapour content in the indoor air was on a level which normally meets the requirements for humidity conditions in the indoor air of a dwelling. The humidity-controlled ventilation system did not in the controlling take into account the removing of other pollutants, such as, for example, radon or gases emanating from furniture and building materials. However, only one of the registered total outdoor air change was below the limit at 0.5 h^{-1} as required in the Danish Building Code [3]. It was 0.46 h^{-1}.

Results of the user satisfaction pilot interviews indicate that there are only few perceived problems concerning humidity in the apartments with humidity-controlled ventilation. However, there may be greater dissatisfaction due to noise and draughts in these apartments due to the construction and positioning of the air intake vents. The questionnaire investigation in the first two weeks' registration period showed that the occupants in 72 % of the humidity-controlled apartments and 45 % in the reference apartment complained about draught. Further investigations based on a questionnaire survey will reveal the extent of user satisfaction with the two ventilation systems.

Conclusion

The functioning of a demand controlled ventilation system with humidity as control parameter has been demonstrated in 16 apartments, of which the humidity condition in the indoor air was compared with 16 identical reference apartments having a constant mechanical exhaust airflow rate according to the Nordic Building Code.

At lower mean outdoor temperatures per day than 9°C, the airflow rate was reduced in the apartments with humidity-controlled ventilation. The minimum airflow rate was obtained at a mean temperature at 1.5°C, where the reduction was 35 %. This reduced the effect for heating 0.75 W/(m^2 net floor area) for each degree the mean outdoor temperature is lower than 6°C.

The mean relative humidity did not exceed 43% which was below the controlling criterion at 45%. The registration of the difference of the vapour content in the indoor and outdoor air did not indicate the occurrence of condensation on the window glass. However, a few more occupants in apartments with humidity-controlled ventilation had observed condensation in the living room when they dried clothes in the room or took a shower. The humidity-control in these apartments was not at its optimum, but simple fundamental physical changes here would be able to improve the regulation system and probably further reduce the energy consumption for heating.

In rooms and apartments where the regulation of the humidity-controlled ventilation was at its optimum, the indoor level of humidity condition in the apartments with humidity-controlled ventilation did not differ from the level in the reference apartments, but the total outdoor air change was less. Hence, the removal of vapour content from the indoor air was more effective with the humidity-controlled ventilation system.

Acknowledgment

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