Performance Evaluation of Humidity-Controlled Ventilation Strategies in Residential Buildings

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ABSTRACT

A high-performance, low-energy ventilation system must combine two opposite demands: an adequate airflow rate for satisfactory indoor air quality (IAQ) and a minimal airflow rate to reduce ventilation heat loss. This research highlights IAQ and energy use in residential buildings where humidity controlled ventilation is applied. How does moisture buffering affect performance, and how much energy can be saved by using this control strategy? The savings in heating energy associated with humidity-controlled ventilation and the exposure to pollutants are benchmarked with the multizone airflow network model CONTAM. These simulations are carried out on a detached residential building with extraction ventilation and self-regulating air inlets.

This study determines the potential energy savings due to humidity controlled ventilation, while the IAQ is compared to the mandatory standards concerning CO_2 and relative humidity.

INTRODUCTION

Nowadays the natural habitat of humans is the indoor environment at home, at work, or in the car. The perception of the indoor air quality (IAQ) in these spaces as "fresh and pleasant" depends mainly on temperature, humidity ratio, CO_2, and the level of thousands of other chemicals in the air (Fanger et al. 1998). Unfortunately, most chemicals, although above an odor threshold, are difficult to measure and therefore impracticable as control parameters. The energy savings possible with CO_2 demand-controlled ventilation (DCV) systems have been well established (10%–80%) (Persily et al. 2003; Emmerich and Persily 1997) but, on the other hand, questions have risen concerning IAQ if only CO_2 is taken into account (Afshari and Bergsøe 2003). Unlike CO_2, the humidity in a building is not solely dependent on the presence of occupants, but also on ventilation with outdoor air, cooking, showering, and washing and drying laundry. Furthermore, high indoor humidity levels often lead to health-related concerns and building damage. Possibly, humidity DCV can overcome some of the flaws of CO_2-based DCV.

Furthermore, economic viability is at stake: carbon dioxide sensors are a lot more expensive than humidity sensors and tend to have a bigger drift. A cheaper control mechanism may possibly result in a rather moderate energy-saving potential but, on the other hand, it will have a larger consumer market. The performance evaluation of ventilation systems has to consider CO_2 as well as humidity. According to EN 13779, Ventilation for Non-Residential Buildings—Performance Criteria, (EN 2004) the relative humidity has to lie between 30% and 70% (see also Harriman et al. [2001]), and the IAQ concerning CO_2 is commonly expressed by IDA classes (see the "Indoor Air Quality" section of this paper).

MODEL

To assess the performance of humidity DCV, simulations were carried out with the multizone airflow network model, CONTAM (2004), on a designed detached residential building. The design was based on a statistical analysis of the newly built dwellings in Belgium. Figure 1 shows the floor plans: the surface area is 162 m and the compactness (the internal volume divided by the surface area) is 1.33. The indoor air temperature

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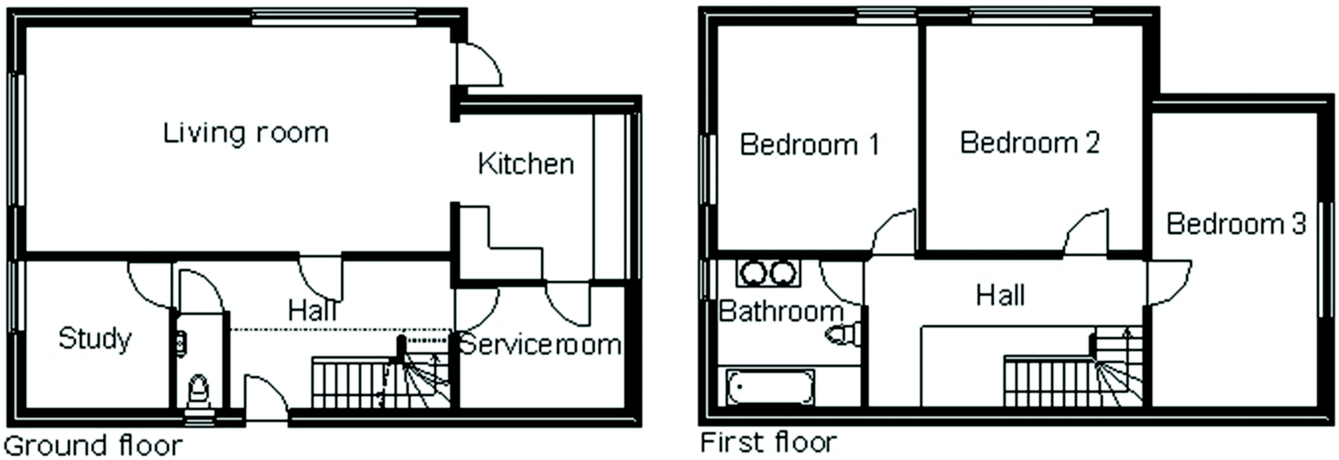

Figure 1 *Floor plans of simulation model.*

is 18°C throughout the whole year because CONTAM (2004) cannot calculate the indoor air temperature based on the weather file. The temperature also has an important influence on the extraction rate because the ventilation system uses the relative humidity as a control parameter. The constant indoor temperature may cause some uncertainty in the stack effect and, hence, in the total airflow rate in the building. On the other hand, pressure differences are primarily dependent on the fan of the ventilation system. Next to that, the influence of the overall temperature is of very little importance if the objective is to compare different ventilation systems. Simulations point out that the effect of local temperature differences (for example, in the bathroom when it's used) is more important. Because the building is detached, the terrain roughness (which considers the influence of the wide surrounding area on the wind speed) is set to 0.20 (country with scattered wind breaks), and the Air Infiltration and Ventilation Center (AIVC) wind pressure coefficient (which considers the influence of the narrow surrounding area on the wind speed) data for low-rise buildings surrounded by obstructions equivalent to half the height of the building were used.

Airtightness

The airtightness is expressed by the n_{50} value: the number of air changes per hour (ach) while there is an indoor-outdoor pressure difference of 50 Pa. In the simulations, we use four different values: $n_{50} = 0.6\ h^{-1} - 1\ h^{-1} - 3\ h^{-1}$, and $11.2\ h^{-1}$. The passive house airtightness standard is $n_{50} = 0.6$. The Belgian ventilation standard NBN D50-001 demands an n_{50} value of maximum $3\ h^{-1}$ for balanced ventilation and $1\ h^{-1}$ for balanced ventilation with heat recovery. The average airtightness of the existing Belgian building stock is $n_{50} = 11.2$ m/h·m. In order to properly model leakage due to stack effect, the facades are subdivided into horizontal strips for each room with two cracks per story. The airtightness of the inner walls is simulated by cracks in the walls and apertures along the doors, while the concrete floors are presumed to be absolutely airtight.

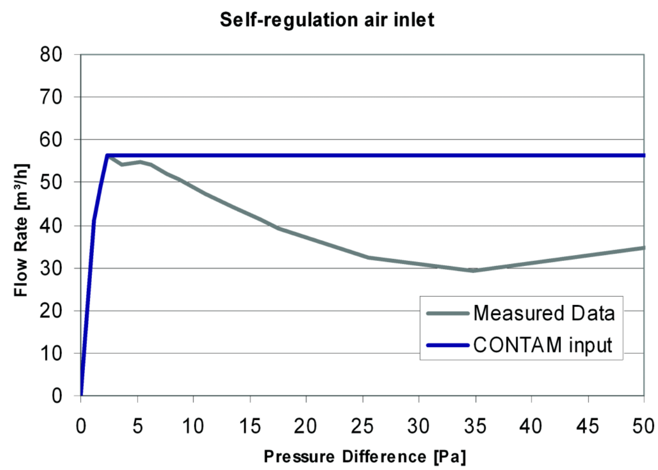

Figure 2 *Self-regulating air inlet.*

Self-Regulating Air Inlets

The living room, study, and bedrooms have self-regulating air inlets above the windows. A pressure difference of 2 Pa results in an airflow rate of 3.6 m/h (for length inlet 1 m), and only increases a little if the pressure difference is higher. The fresh air flows through transit openings from the living areas to the kitchen, toilet, bathroom, and service room. In CONTAM (2004) it is not possible to model the inlet according to measured data: the bicubic spline forces us to use a simplified model with a constant airflow rate when pressure differences exceed 6.5 Pa (see Figure 2). The influence of this change is not to be neglected: 5% of the time the difference in airflow rate lies between 4% and 20% (pressure difference > 6.3 Pa); 1% of the time the difference can rise up to 50% (pressure differences up to 20 Pa). The total average airflow rate through the self-regulating air inlets is about

1% higher because of this. On the other hand, the effect will be of little importance when comparing two ventilation systems.

Contaminant Generation

In the simulations, two parents and two children produce H_2O and CO_2 according to their level of activity (the metabolism is assigned in relation to the type of room the occupant is in). The level of CO_2 in the outdoor environment is fixed, but the relative humidity varies according to the data from the test reference year in Uccle, Belgium (EC 1985).

Moisture Buffering

In CONTAM (2004), a boundary layer diffusion model was used to simulate the effect of moisture buffering. The walls and ceiling have gypsum plaster; other materials, such as wood and textile are not present in the standard model, but the influence of additional buffering is analyzed further on.

VENTILATION

The house is equipped with an extraction ventilation system that extracts 50 m/h in the kitchen, service room, and bathroom, and 25 m/h in the bathroom (nominal flow rate according to the Belgian ventilation standard NBN D50-001 [BIN 1991]). We distinguish two types of control strategies: System C is not demand controlled and maintains a constant extraction flow rate as described above; System C+ varies the extraction flow rate according to the measured relative humidity and presence detection.

There are motion detectors installed in the bathroom, kitchen, and bathroom. In the bathroom and kitchen, the ventilation period is extended with half an hour after the last presence detection; in the bathroom, it is extended 20 minutes. Whenever the motion detectors have sensed a presence, the nominal flow rate will be extracted; otherwise, humidity sensors will control the extraction rate. The humidity sensors are installed in the kitchen, bathroom, and service room. The minimal airflow rate is 20% of the nominal flow, and from 30 to 100% RH the flow rate rises linearly from 20% to 100% of the nominal airflow rate (Figure 3).

The control signals only act on the extraction points, not on the fan. The fan curve is specifically chosen because fluctuating pressure differences would result in a steady airflow rate. This way, the behavior of one extraction point will only have a moderate effect on the other extraction points.

INDOOR AIR QUALITY

To evaluate the IAQ, there are various criteria used in different countries. It is interesting to study those different possibilities and select the most efficient one to compare ventilation systems.

IDA Classes

European Standard EN 13779 (EN 2004) defines a classification of IAQ by CO_2 level. CO_2 is a good indicator of the emission of human bioeffluents, and the classification by the CO_2 level is well established for occupied rooms where smoking is not allowed and pollution is caused mainly by human metabolism. The different categories are shown in Table 1.

Figure 4 shows the IAQ in the living room for system C and system C+ for different degrees of airtightness. The left side represents the system with a constant extraction flow rate, and the right side shows the results for the system with humidity control and motion detection.

The influence of the airtightness on the IAQ in the building is ambiguous. The fraction of IDA class 1, as well as the fraction of IDA class 4, decreases when the airtightness of the building is higher. For one thing, the infiltration and exfiltration rates are reduced, so less fresh air will enter the building. On the other hand, the ventilation system will function better because the actual airflows will correspond to the theoretical design. Wind suction on a façade can have the opposite effect on the airflow in a room and counteract the mechanical extraction. That effect will diminish when the building envelope is more airtight.

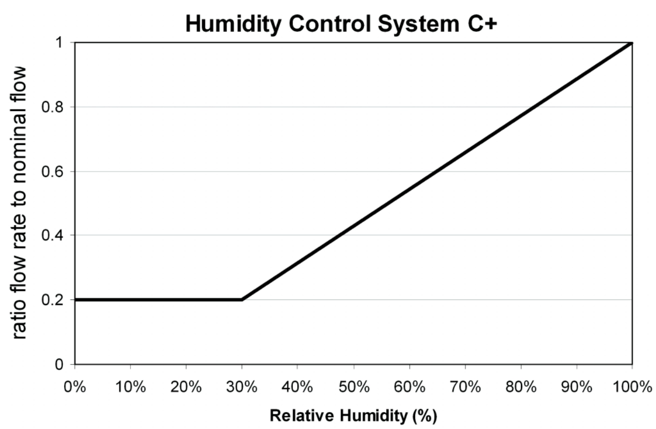

Figure 3 *Humidity control mechanism system C+.*

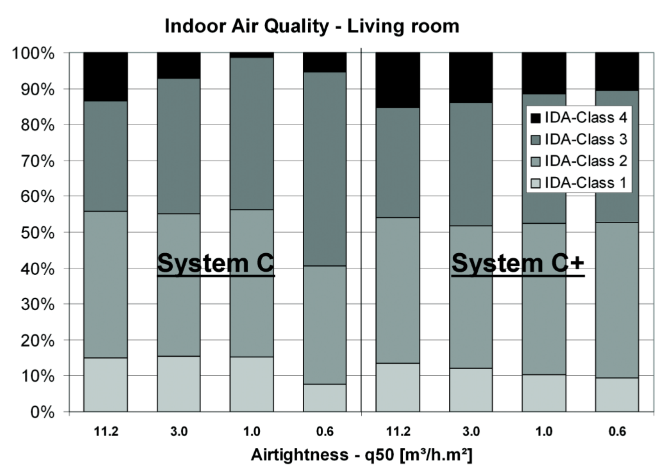

Figure 4 *Indoor air quality living room—IDA.*

Table 1. Indoor Air Quality Categories According to EN 13779

Category	CO_2 Level above Level of Outdoor Air, ppm	
	Typical Range	Default Value
IDA 1	400	350
IDA 2	400–600	500
IDA 3	600–1000	800
IDA 4	>1000	1200

Based on Figure 4, one could conclude that the IAQ might be similar for the two systems, but the mere subdivision in IDA classes can be misleading. In fact, two systems with identical percentages of IDA classes can differ remarkably in IAQ.

French Standard

According to the French standard, *Modalités d'instruction des Avis Techniques sur les systèmes de ventilation asservis* (*Instructions for Technical Regulations on Subjected Ventilation Systems*), one only has to look at the CO_2 levels above 2000 ppm to evaluate the IAQ. For every hour the CO_2 level exceeds 2000 ppm, that concentration is cast throughout an entire year. The standard states that the total amount needs to be less than 500,000 ppmh. Although this method takes the dose-effect-relation into account, it is not clear whether there are very high concentrations over a small period of time, or rather moderate concentrations during the whole year. The physical meaning of this criterion may be less explicit, but on the other hand, it is very practical to compare different ventilation systems to each other.

Belgian Standard

The Belgian ventilation standard NBN D50-001 (BIN 1991) is very prescriptive—there are a lot of regulations for the ventilation system but no criteria for IAQ at all. It is more desirable to define clear performance criteria for indoor air instead of defining the ventilation systems by prescription.

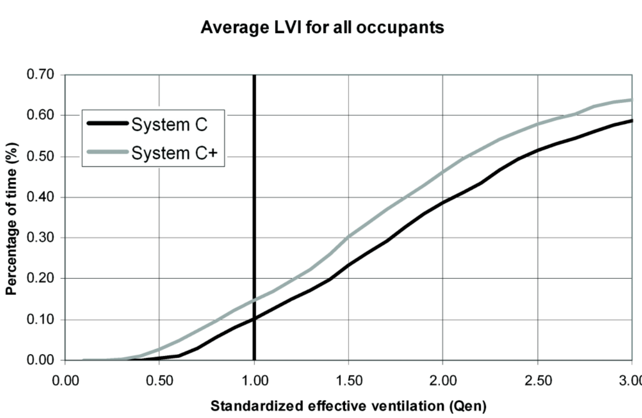

Figure 5 *Low ventilation index.*

Contrary to a prescriptive regulation, a performance-oriented regulation will also stimulate the development of innovative systems.

Dutch Standard

NEN 5128 (NEN 2004), the Dutch standard for energy use in buildings, defines a low ventilation index (LVI), which gives expression to both the extent and the duration of the ventilation deficiency (dose-effect-relation). The LVI can be derived from the histogram of the standardized effective ventilation (Q_{en}). The Q_{en} is defined as the proportion of the concentration limit (for instance, 800 ppm above outdoor concentration) to the actual concentration.

$$Q_{en} = \frac{C_{Limit}}{C_t}$$

The LVI is the total percentage of the time that the indoor concentration exceeds the concentration limit (the area below the curves in Figure 5 for $Q_{en} < 1$).

This one curve gives the opportunity to limit the maximum indoor concentration, limit the LVI, and allow an objective analysis of two systems, without any arbitrary constraints. In this case, the IAQ of the two systems is clearly not equivalent. Currently we use monte-carlo analyses to develop correct values and concentration limits to benchmark new ventilation systems.

Humidity

The indoor air humidity level depends on a number of different factors, including the level of humidity in the outdoor air that is brought indoors by ventilation, human respiration, and activities such as showering, cooking, and washing and

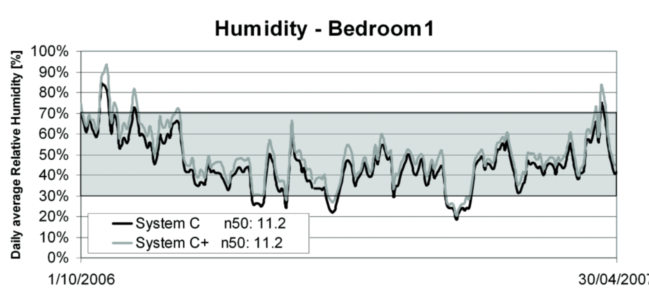

Figure 6 *Relative humidity in Bedroom 1 (leaky building).*

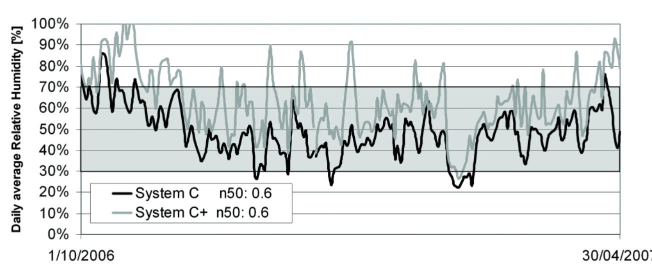

Figure 7 *Relative humidity in Bedroom 1 (airtight building).*

Table 2. Percentage of Time Indoor Air Falls in RH Range

Airtightness n_{50}-value		11.2	3	1	0.6
Living	C	0.88	0.88	0.87	0.87
	C+	0.87	0.87	0.88	0.88
Bathroom	C	0.88	0.88	0.87	0.90
	C+	0.84	0.75	0.68	0.67
Bedroom	C	0.86	0.87	0.88	0.89
	C+	0.87	0.77	0.71	0.67

drying laundry. For a good IAQ, the RH should fall in the range of 30%–70%.

As can be seen in Figures 6 and 7, the difference between systems C and C+ concerning relative humidity is clearly more distinct for airtight buildings. However, the effect is less explicit for the living room and the kitchen. System C results in an IAQ that, for 86% to 88% of the time (in the living room, bathroom, and bedroom), gives a daily average relative humidity in the range of 30% to 70%. System C+ will perform worse for the bathroom and the bedroom, particularly if the building is airtight.

Energy Use

The ventilation heat losses of system C and system C+ show a similar correlation with the airtightness of the building (Figure 8). System C+ allows to increase the energy savings up to 27% for very airtight buildings and 14% for buildings with an average airtightness. However, the absolute energy-saving potential of 1100 to 1200 kWh is independent of the airtightness: the curves in Figure 7 are only translated vertically. Although the ventilation system is primarily controlled by the relative humidity, the effect of airtightness is marginal.

One should bear in mind that these two models have different performances concerning IAQ. Furthermore, simulations point out that while the IAQ is maintained at the same level, more energy can be saved if the peak extraction rate is higher than the nominal airflow rate.

MOISTURE BUFFERING

In CONTAM, a boundary layer diffusion sink/source model (Figure 9) is used to model moisture buffering in different materials. This model has been compared to other buffering models (TRNSYS, Annex 41 simulations). The source/sink model in CONTAM corresponds well to the other models, but it apparently buffers a little bit more than the other models.

In the basic model, only the gypsum plaster of walls and ceilings was entered in the boundary layer diffusion model. To evaluate the significance of moisture buffering for humidity controlled ventilation, two other simulation models were developed. In addition, the comparison of these three degrees of buffering will tell us more about how thoroughly the buffering capacity has to be modeled.

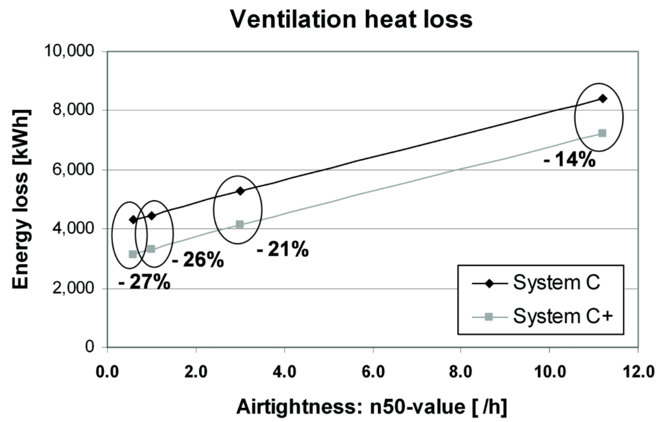

Figure 8 *Energy loss—airtightness.*

The first model (minimal buffering) has no buffering capacity at all. The second model (medium buffering) takes the gypsum plaster of walls and ceilings into account, and the third model (maximal buffering) has the biggest buffering capacity because next to the gypsum plaster, textile and wooden surfaces were also added to the model.

The difference between the minimal and medium buffering is clearly visible: the gypsum plaster dampens out peaks in relative humidity for both high and low values (Figure 10). The effect of additional buffering (textile and wood) is practically none, even in the bathroom. In terms of energy use for system C+, the influence is rather small because the average humidity is about the same for the different models, and the humidity controlled airflow rate is linear to the RH. The simulations point out that system C+ will have an energy demand that is 0.75% higher if moisture buffering is modeled. The influence of the airtightness on the effect of buffering is very small: in terms of energy consumption for system C+, it makes no difference.

CONCLUSIONS

The analysis of simulations of IAQ should be made with great care. A simplified evaluation method can lead to a misinterpretation of the results.

There is a big difference in IAQ between the two systems if one looks at the relative humidity. These differences are perhaps more pronounced than those in CO_2 levels. However, more research has to be carried out on this matter.

System C+ increases the energy savings up to 27% for very airtight buildings and 14% for buildings with an average airtightness. Analysis of the simulations show that the relative humidity is barely different for different degrees of airtightness; furthermore, the average relative humidity indoors differs just about 6%–7% from the average relative humidity of the outside air (when that air is heated up to room temperature).

There is a clear influence of moisture buffering in the model on the relative humidity, but the effect on humidity-

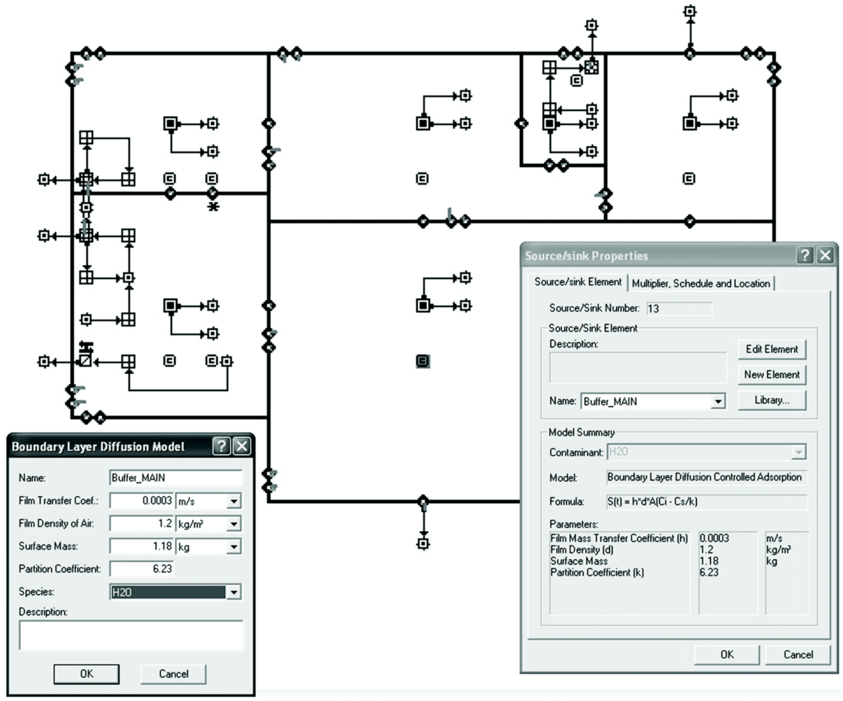

Figure 9 *Boundary layer diffusion model in CONTAM (2004).*

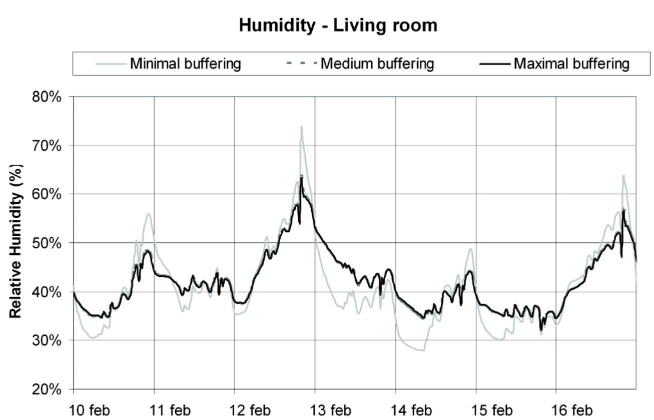

Figure 10 *Relative humidity—living room.*

controlled ventilation in energy use is rather small. The results demonstrate that it is important to add moisture buffering in the simulation model, though it is not necessary to add an elaborate list of buffering materials and surfaces. In this model the walls and ceilings have enough buffering capacity to define the influence on indoor humidity.

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