Investigation on moisture and indoor environment in eight Danish houses

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SUMMARY:
For many years focus has been on reducing the energy demand in buildings. In existing dwellings this is often done by tightening the building envelope e.g. by changing the windows. The tightening leaves the main part of the ventilation of the dwellings in the hands of the occupants as the dwellings then need to be ventilated actively either by natural or mechanical ventilation. Increased focus on energy reduction together with requirements for e.g. thermal comfort indoors may lead to reduced indoor air quality and moisture problems which in turn may cause mould problems.

This paper describes an investigation of the indoor air quality, relative humidity and air change rate in eight Danish houses. The houses were selected as they are all having recurrent problems with condensation on the windows. The houses were built between 1930 and 2007. Some of them have been only slightly renovated where others have been renovated completely. Seven of the eight houses were naturally ventilated and one was equipped with mechanical ventilation system.

In each house room air temperature, relative humidity, and CO_2 concentration were measured in all primary rooms together with the outdoor climate conditions. The average air change rate in each of the houses was measured using passive tracer gas technique, the measurement period being one to two weeks. Based on the measurements the ventilation condition of the houses was compared to requirements in the Danish building regulations in terms of air change rate, to indoor air quality in terms of CO_2 concentration, and to the use of the house in terms of the level of the relative humidity and indoor moisture excess. Furthermore, the moisture production in the houses was estimated and compared to values provided in the literature. A better indoor air quality and lower moisture excess were demonstrated in the houses ventilated according to the Danish building regulations than in houses not fulfilling the requirements. Though, the results showed large variations between the eight houses but also between the parameters examined.

1. Introduction

A large part of the energy used in buildings is used for ventilation. In Denmark the majority of existing dwellings is either naturally ventilated or ventilated through mechanical exhaust systems. In more recent dwellings balanced mechanical ventilation with heat recovery is common, partly due to requirements in the Danish building regulations. The primary role of ventilation is to ensure a good and healthy indoor air quality through removal or dilution of pollutants. In dwellings the pollution typically originates from the residents, from activities of the residents such as cleaning and cooking, from building materials, and increasingly from furniture and equipment.

In office buildings the occupants are the primary pollutant and it is therefore relatively simple to calculate the necessary air change rate to ensure a certain level of air quality. In dwellings the task of determining the appropriate air change rate is more difficult, as can be seen from the fact that different countries make very different requirements.

Since 1982 the fundamental requirement for outdoor air supply in dwellings has been expressed as no less than 0.5 air changes per hour in the Danish building regulations. In 2008 the formulation of the requirement was changed to no less than 0.35 $l/s/m^2$ which is equal to an air change of 0.5 changes per hour with a room height of 2.5 m. With the recent building regulations, being in force as from January 2010, the area used for calculation was changed from net area to gross area, and the required minimum outdoor air supply was changed to 0.30 $l/s/m^2$. That is, the requirement in the Danish building regulations for outdoor air supply in dwellings essentially has not changed from 1982 until today, and the regulations do not take into account neither the occupants nor the use of the dwelling (Erhvervs- og Byggestyrelsen 2010).

This paper describes an investigation in eight Danish houses with the aim to measure the air quality with respect to moisture contents and CO_2 concentration and compare these parameters to the actual air change rate and requirements in the building regulations. Previously, analogous studies have been done; though often the indoor air quality is not assessed by measurement of the CO_2 concentration (see e.g. Norlén et al. (1993), Bergsøe (1994), and Kalamees et al. (2006)).

2. Methods

This study comprises measurements performed in seven single family houses and one sunroom (house #4). The houses were selected as the owners have reported recurrent problems with condensation on the windows. This may be an indicator of high indoor air humidity which may again indicate poor ventilation (Emenius et al. 2000). Characteristics of the houses are summarized in TABLE 1.

TABLE 1. Summary of building characteristics of the eight houses included in the study.

House #	Year of construction	Year of renovation	Area [m^2]	Number of floors	Number of occupants	Ventilation type	Period of measurement
1	1944	1998-2009	300.0	2 + basement	5	Natural	23/2-3/3
2	2006		139.5	1	3	Mechanical	26/1-5/2
3	1967	2007	106.4	1	3	Natural	25/2-5/3
4	2005		16.2	1	2	Natural	22/1-19/2
5	1967	2005 (8m^2 extension)	144.6	1	5	Natural	26/1-5/2
6	2005		129.2	1	6	Natural	19/2-25/2
7	1972		236.2	2 + basement	4	Natural	17/2-23/2
8	1972	1984 and 2005	172.1	1 + partial basement	3	Natural	23/11-8/12

Room air temperature, relative humidity and CO_2 concentration were logged every 5 min during the measurement period of approximately one to two weeks, whereas the air change rate was measured using a passive tracer gas technique, the so-called PFT-technique (PerFluorocarbon Tracer). The PFT-technique was originally developed by Dietz and Cote (Dietz and Cote 1982). The families were encouraged to record observations such as condensation on the windows during the measurement period. Almost no observations were recorded suggesting that the families more or less forgot about the on-going measurements and therefore behaved like they would normally do.

2.1 PFT-technique

The PFT-technique is a passive multiple tracer gas method for ventilation measurements based on the constant emission principle. Tracer gas is emitted passively and continuously with a known rate from a small tracer gas source, while determination of the average tracer gas concentration in the indoor air is determined through the use of passive adsorption tube samplers. The tracer gas source is a small aluminium shell containing liquid tracer. The source is closed at one end with a silicone rubber plug through which the tracer diffuses. The adsorption tube sampler is a glass tube containing an adsorbent material similar to activated charcoal. The samplers are analysed in the laboratory through thermal desorption and gas chromatography.

With the PFT-technique it is possible to use several different tracer gases simultaneously. A building may be split into zones, making it possible to determine not only the total air change rate of the building, but also the air change rate of each zone as well as exchange of air between the zones. Depending on the measuring circumstances the measurement period may range from less than a day up to several months (Bergsøe 1992) and (Dietz et.al. 1986).

2.2 Measurement of temperature, relative humidity and CO_2

The room air temperature, relative humidity and CO_2 concentration were measured using a wireless system from Eltek. In each house the sensors were distributed evenly throughout the house. An example of the location of the Eltek sensors, tracer gas sources and adsorption tube samplers in one of the houses is illustrated in FIG 1.

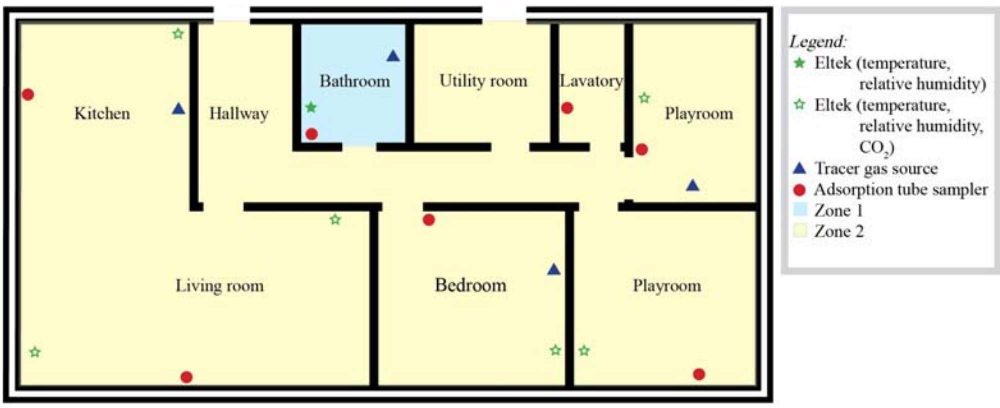

FIG 1. Example of location of measurement equipment in house #3. The Eltek system was used for measurement of temperature, relative humidity and CO_2 concentration, whereas the PFT-technique was used for measurement of air change rate. For the measurement of air change rate the house was divided into two zones by use of two different tracer gases.

2.3 Estimate of moisture production

An estimate of the moisture production in the houses is done according to the following equation:

$$MP = \left(\frac{\sum_i x_i V_i}{\sum_i V_i} - x_e \right) \rho n \sum_i V_i \qquad (1)$$

Where x_i average vapour content of air in room i (kg vapour/kg dry air)
x_e average vapour content of outdoor air (kg vapour/kg dry air)
ρ density of dry air at room air temperature (kg/m^3)
V_i volume of room i (m^3)
n total air change rate of the house (h^{-1})

From the equation the mass of moisture removed by ventilation is roughly estimated. The measurements were conducted after a longer period with low humidity of the outdoor air (except for house #8). It is therefore anticipated that the amount of moisture removed by ventilation equals the moisture production in the house.

3. Results

3.1 Outdoor air supply

In TABLE 2 the outdoor air supply, calculated based on the passive tracer gas technique, is displayed. It is evident that in four of the houses, including the one with mechanical ventilation system (house #2), the outdoor air supply is lower than stipulated in the building regulations. Furthermore, it appears that the outdoor air supply per m^2 may not be an appropriate measure of how to obtain satisfying indoor climate. This is illustrated by the fact that the outdoor air supply per m^2 of two houses can be approximately equal whereas the air supply per person in the less ventilated house is nearly only half of that in the most ventilated house, as observed for house #1 and #3 and for house #5 and #7.

The result of a measurement using the PFT-technique is the average outdoor air supply during the measurement period. Thus, temporal variations of the ventilation rate cannot be determined.

TABLE 2. Air change rate and outdoor air supply in the houses.

House #	Air change rate [h^{-1}]	Outdoor air supply [m^3/h]	Outdoor air supply per person [m^3/h/person]	Outdoor air supply [$l/s/m^2$]	Difference from building regulations [$l/s/m^2$]
1	0.3	205	41	0.19	- 46%
2	0.3	139	46	0.28	- 20%
3	0.3	72	24	0.19	- 46%
4	1.5	60	30	1.03	194%
5	0.7	231	46	0.44	26%
6	0.4	109	18	0.23	- 34%
7	0.7	369	92	0.43	23%
8	0.8	307	102	0.50	43%

3.2 Indoor air quality

The indoor air quality may be evaluated based on the CO_2 concentration in the room air. In TABLE 3 results of the CO_2 measurements in the eight houses are summarized. The measurements have been categorized according to DS/CEN/CR 1752 (Dansk Standard 2001). Generally high CO_2 concentrations were measured in house #2, #3 and #6, which is consistent with the fact that the outdoor air supply in these houses was low compared to the requirement in the building regulations. Furthermore, high CO_2 concentrations were measured in the bedrooms and playrooms in six out of the seven houses containing such rooms. It may thereby be interpreted that the ventilation in rooms where people sleep has a tendency to be too low.

Comparing house #1 and #3, the CO_2 concentration is significantly higher in house #3 in spite of similar air changes in the two houses when expressed in relation to the area. However, when considering the air change per person instead, the higher CO_2 concentration measured in house #3 may be explained, as the air change per person in this house is only half the air change per person in house #1. A similar tendency is observed between the measurements of house #5 and #7, though it is less distinct. The CO_2 concentrations in the kitchen and living room of house #7 are very low. This may indicate that these rooms are well ventilated, which is not observed in house #5.

TABLE 3. CO_2 concentration, relative humidity, and indoor moisture excess in the houses. The CO_2 measurements are categorized according to DS/CEN/CR 1752, where the outdoor CO_2 concentration is set to 370 ppm. The indoor moisture excess is calculated as the difference between indoor and outdoor absolute humidity.

House #	Room	Cat. A: $[CO_2]$ < outdoor conc. + 460ppm [%]	Cat. B: $[CO_2]$ < outdoor conc. + 660ppm [%]	Cat. C: $[CO_2]$ < outdoor conc. + 1190ppm [%]	Out of category: $[CO_2]$ > outdoor conc. + 1190ppm [%]	Mean relative humidity [%]	Indoor moisture excess [g/kg dry air]
1	- Bedroom (1st floor)	34	45	15	6	54	2.7
	- Playroom 1 (1st floor)	30	30	38	1	51	2.7
	- Playroom 2 (1st floor)	66	20	10	4	50	2.7
	- Kitchen (Ground floor)	56	39	5	0	41	3.3
	- Living rm. (Ground fl.)	25	42	33	1	43	3.7
2	- Bedroom	32	18	18	31	42	3.9
	- Playroom 1	38	8	20	34	36	3.3
	- Playroom 2	47	28	21	4	35	3.1
	- Kitchen	37	27	34	2	37	4.0
	- Living room	29	30	40	1	36	3.6
	- Utility room	43	42	16	0	36	3.3
3	- Bedroom	32	4	26	38	43	2.9
	- Playroom 1	34	5	42	19	43	2.9
	- Playroom 2	31	6	36	26	40	2.8
	- Kitchen	26	17	40	18	40	2.8
	- Living room (sensor 1)	28	16	36	20	38	2.6
	- Living room (sensor 2)	24	10	44	23	41	2.6
4	- Sunroom	76	13	7	4	41	2.6
5	- Bedroom	58	12	30	0	37	2.3
	- Playroom 1	35	20	41	3	43	2.9
	- Playroom 2	28	22	40	10	44	3.0
	- Living room 1	70	17	11	2	37	2.4
	- Living room 2	51	32	17	0	40	2.6
6	- Bedroom	36	10	19	35	44	3.0
	- Playroom 1	4	8	45	44	43	3.8
	- Playroom 2	8	6	47	39	41	3.5
	- Playroom 3	7	6	26	61	44	3.7
	- Kitchen-dining area	4	9	56	32	41	3.8
	- Living room	7	7	32	54	40	3.7
7	- Bedroom (1st floor)	61	8	10	21	36	2.7
	- Playroom 1 (1st floor)	56	10	23	11	36	2.4
	- Playroom 2 (Basement)	81	4	6	8	28	1.7
	- Kitchen (Ground floor)	97	3	0	0	31	2.1
	- Living rm. (Ground fl.)	100	0	0	0	29	1.9
8	- Bedroom	43	16	22	19	58	2.0
	- Playroom	33	26	27	13	54	2.1
	- Kitchen	52	34	14	0	45	2.5
	- Living room	66	24	11	0	51	2.2
	- Office	54	16	23	7	56	1.9
	- Basement	97	2	1	0	48	2.1

3.3 Relative humidity and indoor moisture excess

The mean of the relative humidity measured in the eight houses can be observed in TABLE 3 together with the indoor moisture excess. It is evident that the highest humidity levels are measured in the bedrooms or playrooms of the individual houses. However, when considering the indoor moisture excess, no significant pattern is observed in the differences between night zones (bedrooms) and day zones (living rooms and kitchens). This has also been observed by Kalamees et al. (2006) in a study of timber-frame detached houses.

In general, the relative humidity measured in all the houses is at a normal level considering the season. The low air change rates and high CO_2 concentrations measured in house #2, #3 and #6 are not directly reflected in the relative humidity. This may be expected as the humidity in a house not only depends on the outdoor air supply, but also on the indoor air temperature and moisture production etc. On the contrary, the indoor moisture excess is generally higher in the four houses ventilated less than required by the building regulations (houses #1, #2, #3, and #6) than in the houses ventilated more than required.

The measurement of relative humidity in a house is exemplified in FIG 2. The graphs illustrate how the mean relative humidity provided in TABLE 3 cover significant temporal variations.

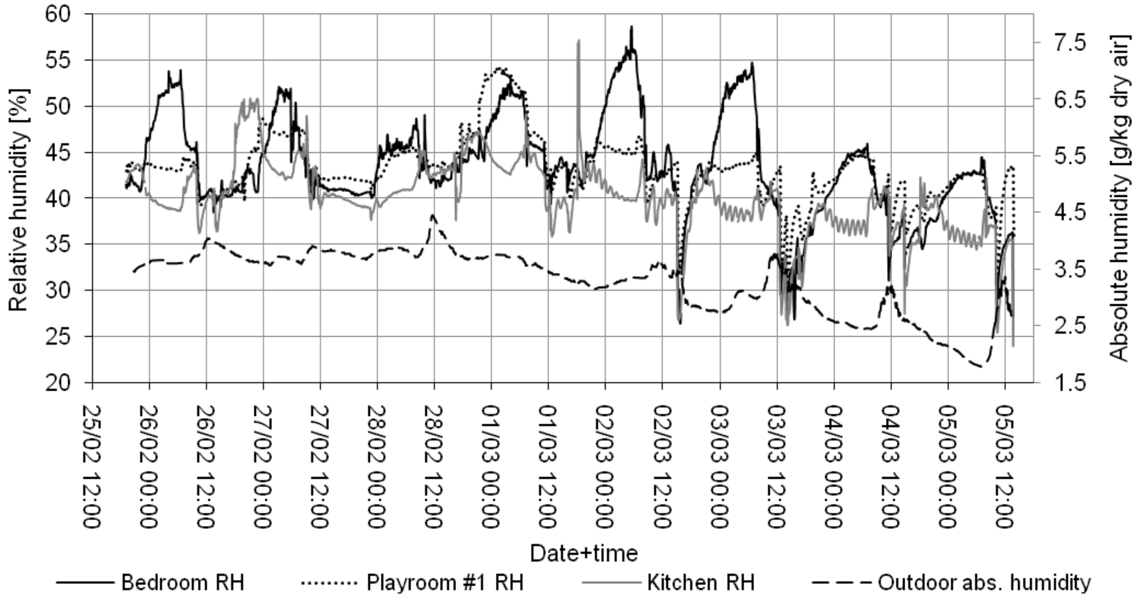

FIG 2. Indoor relative humidity of selected rooms in house #3 and outdoor absolute humidity.

3.4 Moisture production

The moisture production in the eight houses was estimated according to the procedure described in Section 2.3. TABLE 4 lists the estimated moisture production which, in five of the eight houses, is significantly higher than given in literature by e.g. Koch et al. (1987). The relatively low moisture production in house #3 and #6 may explain why low relative humidity is measured simultaneously with low air change rate and high CO_2 concentration in these houses. This supports previous studies, which show that the ventilation rate is adapted to the moisture production (Gunnarsen 2001).

TABLE 4. Moisture production in the eight houses along with expected values from Koch et al. (1987).

House #	Moisture production [kg/day]	Moisture production per person [kg/day/person]	Expected moisture production from Koch et al. (1987) [kg/day]
1	18.3	3.7	10.2
2	14.6	4.9	6.8
3	5.9	2.0	6.8
4	4.5	2.2	5.1
5	19.8	4.0	10.2
6	11.8	2.0	12.0
7	22.2	5.6	8.5
8*	20.2	6.7	6.8

* The measurements in house #8 were not conducted after a longer period with low outdoor humidity. Hence, the moisture production may be significantly overestimated in this case.

3.5 Air tight building envelope

House #3 was completely renovated in 2007. After the renovation the house is quite air tight. The air enters through outdoor air inlets in the windows and is extracted through kitchen, bathroom and lavatory. However, the residents often close the inlets due to draft. This results in the unfavourable air flow pattern shown in FIG 3. When the exhaust hood in the kitchen is on, the air flows from the bathroom and lavatory, and when the fan in the bathroom is running the air flows from the kitchen and the lavatory etc. By this example it is shown how tightening of the building envelope may result in unfavourable air flow in a house if the residents are not aware of the need to actively ventilate the house.

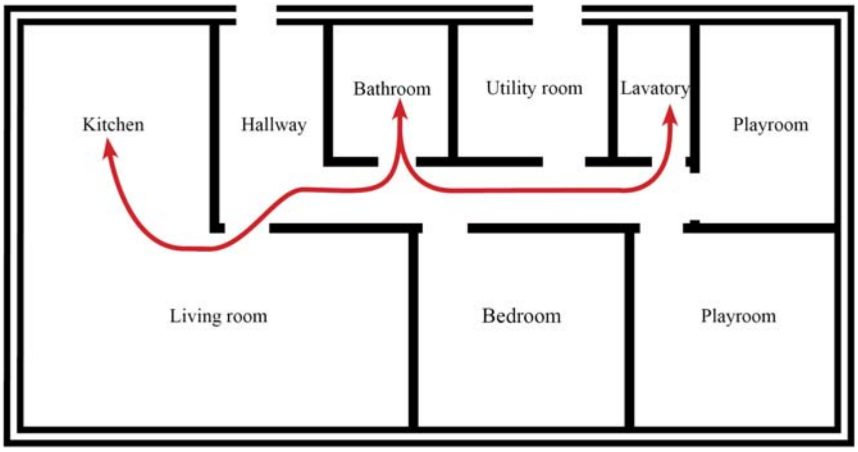

FIG 3. Predominant airflow with closed fresh-air vents in test house #3 after renovation.

4. Conclusion

The ventilation conditions in eight houses were evaluated according to five parameters; namely outdoor air supply, CO_2 concentration, relative humidity, indoor moisture excess, and moisture production. In four of the eight houses it was established by the PFT-technique that the averaged outdoor air supply was lower than required by the Danish building regulations. It was shown that generally the houses ventilated according to the regulations had a better indoor air quality and a lower indoor moisture excess than the houses with an outdoor air supply less than required from the regulations. Though, it has also been shown that the requirements in the building regulations regarding outdoor air supply as a function of the living area in itself cannot ensure adequate indoor air quality. It is necessary that the occupants act reasonable and contribute through airing and sensible behaviour.

The bedrooms and playrooms were determined to have the lowest indoor air quality and in most cases also the highest relative humidity. However, the measured relative humidity in the houses was in general not high despite the finding that the estimated moisture production in some houses was significantly higher than expected from literature. In summary, the current study on moisture and indoor environment provides no clear pattern explaining why condensation occurs on the windows in the eight houses.

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