Moisture safe cold attics - Assessment based on risk analyses of performance and cost

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KEYWORDS: *Mould growth, probabilistic, risk, weather, attics, life cycle cost, drying potential*

SUMMARY
Problems with high humidity levels and mould growth in cold attics have been increasing over the last few years. A recent Swedish study showed that as many as up to 60 – 80 % of the single-family houses in Västra Götaland (largely, the Gothenburg region) are showing significant mould growth and thereby risk developing serious moisture problems. The high humidity levels are to a large extent a consequence of the increasing demand on energy efficiency. Houses are frequently retrofitted with additional attic insulation, which leads to a colder attic space and hence a higher humidity. Furthermore, furnace heating is often replaced in favour of heat pumps or district heat. This may alter the air-pressure balance of the house, resulting in an increased thermal pressure on the ceiling with subsequent air-leakage up to the attic. Also newly built attics have problems. A risk assessment of the risk for mould growth is performed for different design of the attic. Also a simplified life cycle cost is estimated for the different design alternatives. The alternative with controlled ventilation is estimated to be risk free with lowest life cycle cost. Roof insulation gives low risk for mould growth in northern part of Sweden.

1. Introduction

Problems with high humidity levels in cold attics have been remarkably increasing in Sweden over the last decade. Beside clear evidence – the significant mould growth on the wooden parts of cold attics, which is recently confirmed in about 60-80 % single-family houses in Västra Götaland region (largely, the Gothenburg region; (Ahrnens C., Borglund E., 2007), mould odours in indoor air seem to be one of the most frequent side effects. Thus, cold attics are together with crawl spaces singled out as the two worst constructions in existing Swedish buildings with large existing and future mould problems.

The high humidity levels are to a large extent a consequence of the increasing demand on energy efficiency. Houses are frequently retrofitted with additional attic insulation, which leads to a colder attic space and hence a higher humidity (Hagentoft et.al. 2008). Leaks of indoor air up to the attic through the attic floor, and the under cooling of the roof due to sky radiation, increase the problem (Holm and Lengsfeld 2006, Sanders et. al 2006, Essah et. al 2009). The moist air might condensate at the underlay and small droplets of liquid water can build up. The water will then be absorbed and accumulated in the surface area. High moisture content can even lead to rot.

Another important moisture source influencing the attic hygrothermal condition is the water vapour in the surrounding outdoor air. The advice given to the building sector in Sweden today is to have a not too high or not too low ventilation rate, by outdoor air, of the attic. A too high ventilation rate, in combination with under cooling, results in high relative humidity (Sasic 2004). Too low ventilation is also risky in case of construction damp or leaky attic floor (Arfvidsson and Harderup 2005, Sanders 2006, Essah 2009). The optimal air exchange rate varies with the outdoor climate, and fixed ventilation through open eaves and/or gable and ridge vents are not always the best choice (Hagentoft et. al 2008,2011, 2012).

The results from a recently finished SBUF-financed Swedish research project *Risk assessment for Cold Attics* is presented in this paper (Hagentoft, Sasic, 2103).

2. Probabilistic Analysis – Type of attics

The probabilistic model of attic performance presented in this paper uses validated deterministic models for the heat and moisture transfer (see section 4). The Monte Carlo method will be used to calculate the maximum mould growth index for multiple randomly chosen and simulated whole year. One of 30 weather data years (1961- 1990) with hourly values will be selected randomly for each simulation. The attic is assumed to be damaged by mould growth if the Mould Growth Index (MGI) according to Hukka and Viitanen (1999) exceeds 1.

The reference case is represented by the conventional design of a cold attic today. It has a -sloped roof (between 10 to 30 degrees), which is built from the inside starting with 22 mm wooden T&G board, moisture tight board, litter and batten and counter batten and roof tiles. The cold attic floor is insulated with 400 mm loose fill insulation. The reference house is ventilated by 20 mm wide open slots along the eaves. The building is five storeys high (a multi-family house), has an attic floor area of 220 m^2. There is an exhaust ventilation system in the building resulting in a ventilation rate of 0.5 h^{-1}. The leakage of the building envelope at 50 Pa is 0.6 litre/m^2/s. Two alternative attic floor constructions are considered; a 200 mm thick concrete floor with a vapour barrier on top or a wooden frame construction with gypsum board and a vapour barrier. In the simulations, three alternative airtightness's of the attic floor are considered; Totally tight, tight (0.06 air exchanges of the indoor air at 50 Pa alternatively expressed as a specific leakage area of $6.4 \cdot 10^{-6}$ m^2/m^2) or leaky (0.3 air exchanges of the indoor air at 50 Pa/$3.8 \cdot 10^{-5}$ m^2/m^2). Different Swedish locations are considered and the orientation of the building (North, East, West and South) is varied. The indoor moisture supply is either low (1± 0.5 g/m^3) or medium (3± 0.5 g/m^3), and normally distributed.

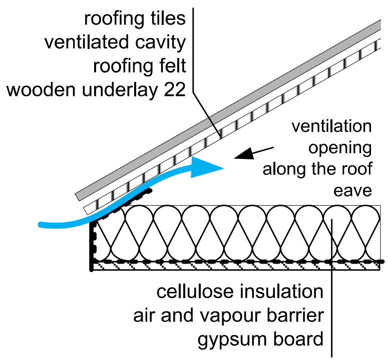


FIG 1. The conventional cold attic - the traditional reference construction.

The following alternative designs are used (see also Figure 2):

- Conventional
- Thermally insulated roof
- Controlled ventilation
- Diffusion open membrane
- Moisture buffering insulation material

3. Risk indicators for alternative design – Results in a nutshell

In the next chapter, some results for the hygrothermal performances of the attic are presented for some cases. Here, we present the findings in terms of a risk levels for the different construction designs. The color used are then representing:

- Risk free (Green)
- Low risk (Yellow)

- Semi high risk (Orange)
- High risk (red)

In Figure 2 the risk levels of the various designs are presented together with some requirements for the risk evaluation. One important finding is that it is very important to dry out the building damp immediately after construction for all cases.

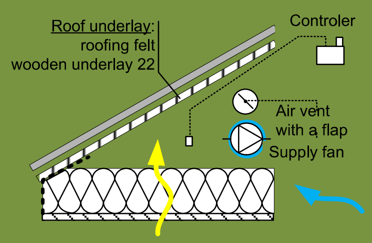
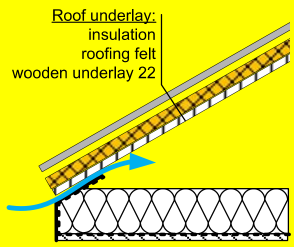
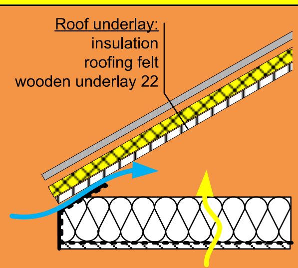
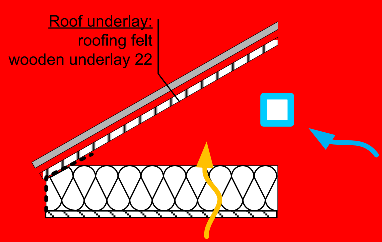
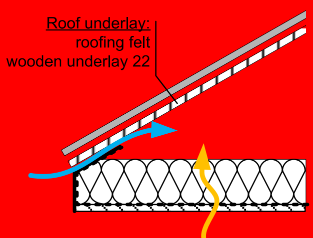
	Cold attic construction	Requirements and sensitivity
Risk free	 Controlled mechanical ventilation	• The airtightness of the attic should be at least 10 1/h@50Pa • Ventilation should start directly after completeness of attic construction • Requires alarm function for failure of mechanical devices • Lowest total life cycle cost
Low risk	 Insulated roof, good air tightness of the attic floor	• Requires durable solution for the airtightness of the attic floor. • Works better at low moisture excess in the building (well ventilated housing - preferably exhaust only mechanical ventilation system). • Sensitive to the building orientation. • Some sensitivity to the local and future climate. • Should be supplemented with dehumidifiers in the construction phase to eliminate built-in moisture.
Semi-high risk	 Insulated roof, some air leakage in the attic floor	• Works better at low moisture excess in the building (well ventilated housing - preferably exhaust only mechanical ventilation system). • Sensitive to the local and future climate. • Should be supplemented with dehumidifiers in the construction phase to eliminate built-in moisture.
High risk	 Reduced ventilation – only through gable vents; air tight roof eaves.	• Extra sensitive to the lack of air-tightness in the attic floor and high moisture excess in the home. • Should be supplemented with dehumidifiers in the construction phase to eliminate built-in moisture. • Sensitive to future climate.
High risk	 Traditional cold attic	• Extra sensitive to the lack of air-tightness in the attic floor and high moisture excess in the home. • Sensitive to future climate. • The most expensive technical solution when lifecycle cost is assessed. • Should be supplemented with dehumidifiers in the construction phase to eliminate built-in moisture.

FIG 2. Summarized risk levels of the various designs presented together with some requirements.

4. Hygrothermal performance

Only some samples of results from total findings in the project will be given in this chapter. The complete report (In Swedish) can be found in the reference list (Hagentoft, Sasic, 2013), with a direct link.

Figure 3 shows a number of simulations based on randomly chosen years. In the simulations the cold attic starts from dry conditions, in the middle of the summer. The risk assessment is based on the fraction of simulations that results in a mould growth index exceeding one. In this example 17 of total of 128 simulations results in a failure, i.e. the risk for mould growth is 13% (17/128=0.13).

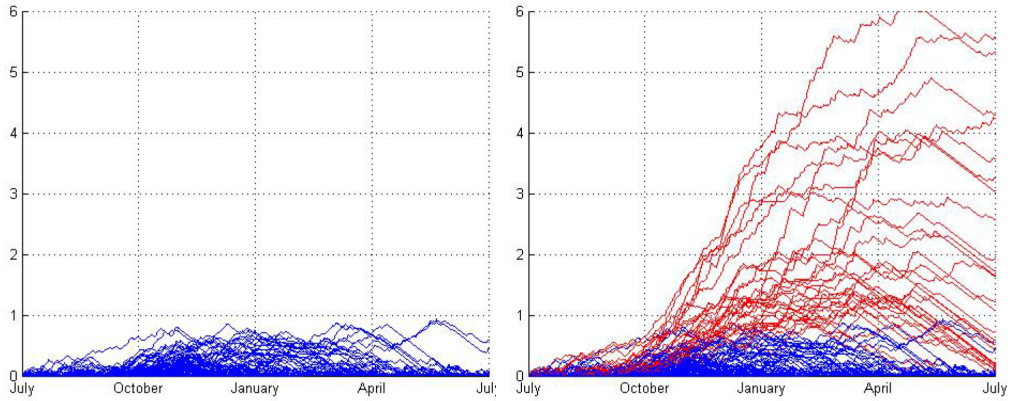


FIG 3. Example of simulation results for randomly chosen years and input parameters. The figure to the left represent the damaged free simulations and the additional ones in the right hand figure represent additional cases with mould growth.

The cases with controlled ventilation do not result in any mould growth exceeding 1. The second best alternative is represented by the case with insulation on the roof. Table 1 shows the results for some of these cases.

TABLE 1. Results from the probabilistical simulations. The table presents the maximum mould growth rates for two different slope angles of the roof (10 and 20 degrees). The roof structure is covered with 0,1 m cellular plastic insulation. The location is Gothenburg or Stockholm and the orientation of the building is varied. For the Stockholm case with a tight attic floor no mould growth is registered.

	Leaky attic floor				Tight attic floor			
Gothenburg, roof slope 10°	N	S	E	W	N	S	E	W
Average of max MGI*	1.40	1.09	0.81	0.83	0.28	0.23	0.08	0.10
Risk that max MGI* >1, (%)	41	33	24	25	8	5	0	0
Gothenburg, roof slope 20°								
Average of max MGI*	1.74	1.07	0.95	1.09	0.34	0.25	0.11	0.08
Risk that max MGI* >1, (%)	50	33	30	29	9	5	0	0
Stockholm, roof slope 10°								
Average of max MGI*	0.55	0.38	0.70	0.50				
Risk that max MGI* >1, (%)	17	12	17	13				
Stockholm, roof slope 20°								
Average of max MGI*	0.68	0.38	0.54	0.57				
Risk that max MGI* >1, (%)	20	9	12	14				

* max MGI means the maximum MGI during one year of simulations.

5. Simulation tool

SimpleColdAttic is a stand-alone software for HAM-simulations of cold attic temperature, relative humidity as well as mould growth index. The program can simulate both in deterministic as well as in probabilistic (random) mode. With the program similar cases as presented here in this paper can be analysed. The program is based on a simplified HAM-model for an attic, theory can be found in (Hagentoft, 2011) and (Hagentoft and Sasic, 2011).

The free software can be down loaded from: http://www.byggnadsteknologi.se/downloads.html.

6. Life cycle cost

Table 2 shows the final results for the total cost (life-cycle cost) for alternative construction designs of the attic. Location, airtightness of the attic floor and moisture supply is varied as random parameters in the calculations.

TABLE 2. Total cost (in SEK) for attic floor and roof (104 m^2) for the case with a one-family residential building. In the case with roof insulation, the insulation thickness of 0.1m is considered. The roof slope angle is fixed to 20 degrees and the orientation is North-South.

Alternative Design	Base Investment	Operational Cost	City	Airtightness Moisture supply	Risk MGI>1	Damage Investm.	Yearly Cost
Conventional	76380	0	Gothenburg	Any	100%	38400	5739
Ins. roof	94135	0	Gothenburg	Good Low	10%	3840	4889
Ins. roof	94135	0	Stockholm	Not good High	50%	19200	5657
Ins. roof	94135	0	Stockholm	Good Low	0%	0	4697
Ins. roof	94135	0	Stockholm	Not Good High	20%	7680	5081
Controlled ventilation	88427 (80927)	600	Anywhere	Any	0%	0	4639

The yearly cost is based on a 5% interest rate on investments. The damage investment represents a simplification representing the cost for the fraction of the buildings damaged that has to be cleaned and added a controlled ventilation system. For the controlled ventilation the fan is assumed to be replaced after 15 years which gives a yearly operational cost of 500 SEK. The use of electricity for the fan ads further 100 SEK to the yearly cost. The investment cost for the controlled ventilation, in brackets, is the value after reduction of cost for exchange of the fan (7500 SEK) which is given as a yearly cost instead. Ill-will (bad-will) is not included. Initial cost for drying of building damp is included with 5000 SEK (for the cases with conventional solutions or insulated roof). No inflation is considered, the numbers represent the real value.

7. New findings on drying potential for cold attics and ventilated structures

Although one could expect a close correlation between the mould growth risk in cold attics and outdoor climate, specifically outdoor temperature and solar radiation intensity, previous investigations (Nik et al., 2012) and also the results presented in Table 1 show that such correlation is not straightforward. The results suggest that the risk is also correlated to the ventilation flow rate through the attic, which is determined by the wind and the orientation of the attic. This is further investigated by the means of a *drying potential*, $D\Pi$, a new performance criterion which can be seen as an upgraded Π-factor (Hagentoft, 1993,; Hagentoft and Harderup, 1996). For the period between the times t_a and t_b, $D\Pi$ is found as

$$\mathrm{D\Pi} = \frac{1}{t_b - t_a}\int_{t_a}^{t_b} \widetilde{R}(w,\theta)\cdot\left(v_{sat}(T_{eq}) - v_{out}\right)dt, \quad 1/\widetilde{R}(w,\theta) = 1/R_a(w,\theta) + \frac{1}{A/Z(R_a)} \tag{1}$$

Where T_{eq} equivalent outdoor temperature, (°C)
v_{out}, v_{sat} water vapour content in outdoor air and at saturation, (g/m³)
R_a air flow rate through the ventilation opening in the attic, (m³/s)
w wind speed, (m/s)
θ angle between the wind direction and the azimuth of the ventilation opening, (deg)
A area of the roof slope (only shed roofs), (m²)
Z resistance to convective moisture transfer between the air and the roof slope, (s/m)

While Π-factor is basically calculated from the weather parameters and radiation surface conditions, DΠ accounts in addition for the attic geometry and ventilation flow rate through the attic. Figure 4 shows DΠ for a conventional cold attic, which can be located in Gothenburg or in Stockholm, and over the period of 1975-2100. The climate data are obtained from the climate scenarios RCA3-ERA40 (1975-2004) and RCA3-ECHAM5-A1B-1 (2010-2100), (Nik et al., 2012). The geometry and roof slope (20 deg) of the attic are same in every case, while the orientation of the roof varies. The values included in the figures refer to annual mean DΠ, g/(m²·h). Based on the results, the lowest DΠ is found for the attic in Gothenburg with north roof orientation. At the same location, DΠ for the attics with west and east roofs is approximately the same, and twice the value for the north roof. Finally, DΠ for the south roof is close albeit somewhat lower in the later period than of the west and east roof. By comparing these findings with the mould risks from Table 1, we can conclude that the lower DΠ, the higher risk for mould growth and vice versa.

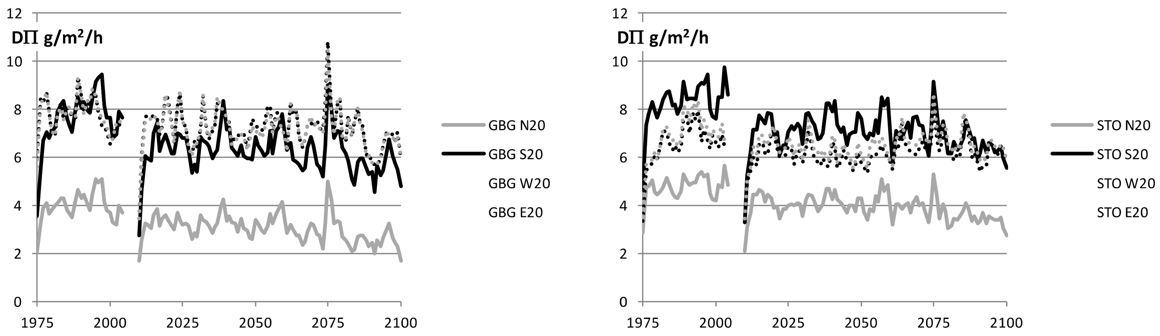


FIG 4. Drying potentials for a cold attic with different roof orientation and geographical location. The results up to 2004 are obtained with the climate data from RCA3-ERA40. From the vertical dashed lines, the results are obtained with the climate data from RCA3-ECHAM5-A1B-1.

The results for the cold attic in Stockholm are similar, with one exception that the DΠ for the south roof is somewhat higher than for the west and east roofs. Even these results are well correlated with the mould risks from Table 1, i.e. the largest DΠ (for the south roof) corresponds to the lowest risk (also the south roof).

We can also observe a declining trend of DΠ over time that can be interpreted as the predicted climate changes will increase the risk of mould growth in the attic.

For comparisons of drying potentials between different locations, a normalized drying potential is used:

$$\mathrm{nD\Pi}_j^{City,period} = \frac{30^{-1}\cdot\sum_{i=year}^{year+30}\mathrm{D\Pi}_j^{City,i}}{\overline{\mathrm{D\Pi}}_W^{LUND,1975-2004}} \tag{2}$$

Where

City, period Location and 30-year period for which nDΠ accounts for
j roof orientation, N, S, E, W

year	start year, for example 2010, 2014, 2070
$D\overline{\Pi}_{W}^{LUND,1975-2004}$	30-year averaged DΠ at a location with the highest drying potential in the country (*LUND*), in the past, 1975-2004, and for the roof orientation with the highest average drying potential at the same location (*W*=west)

The normalized drying potential is a relative measure that takes values between 0-1, where 0 means no drying potential and 1 the maximum potential for the climate in Sweden. Figure 5 shows the normalized drying potential for four representative cities in the country and for the past and predicted future climate conditions. Based on the past climate data (1975-2004), the maximum drying potential for a cold attic is found in Lund, for the west or east roof orientation, and the minimum in Östersund for the north roof orientation. The south roof direction in Lund has the next largest normalized drying potential (0.9). South, west and east roof orientations in Gothenburg and Stockholm show moderately high nDΠ (0.6-0.7), while the north roof direction has a low potential (0.5 or lower) at all locations. As the latitude increases, nDΠ decreases, reaching the lowest values in Östersund for all roof directions.

Although the predicted future climate changes indicated a noteworthy increment of outdoor air temperature (see Figure 5), the normalized drying potential at all locations and directions decreases. The main reason for this is increasing outdoor air humidity, which is about 2 g/m^3 larger in 2070-2100 than in the past period.

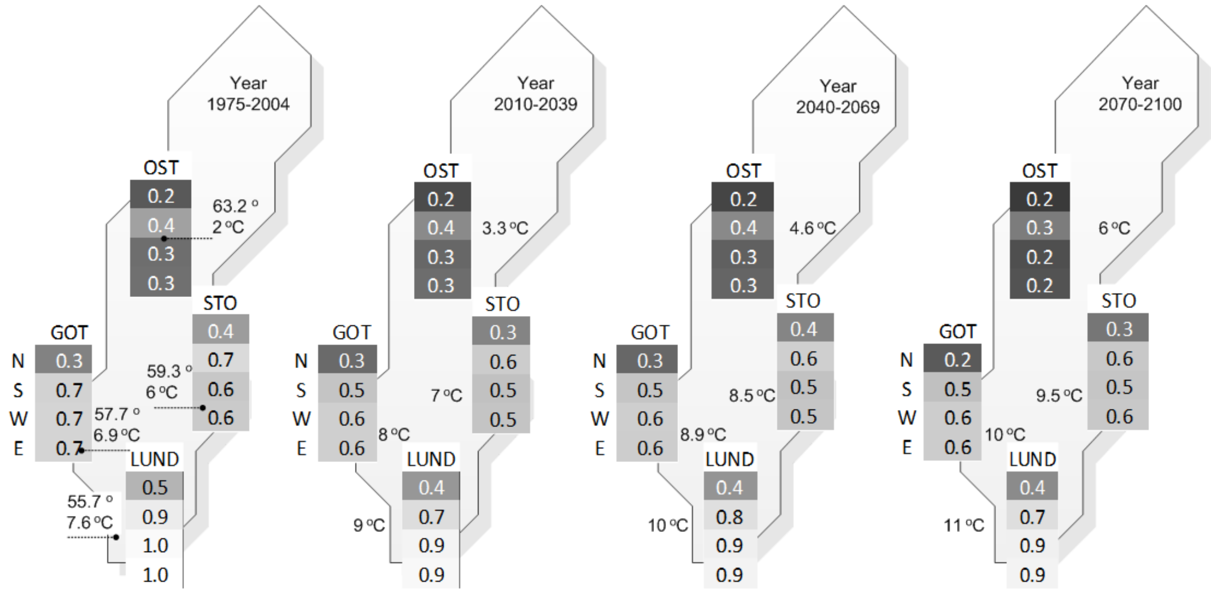


FIG 5. Normalized drying potentials for a cold attic with different roof orientations and geographical locations in Sweden (GOT=Gothenburg;STO=Stockholm;OST=Östersund and LUND). For each location, the latitudes and 30-year average of annual outdoor temperatures are shown.

8. Conclusions

The results from the research project gives:

- The moisture safety of a cold attic is improved if: the attic floor is airtight, building damp is removed directly after the building has been erected, the indoor environment is well ventilated and the attic has a positive pressure in relation to the dwelling.
- Conventionally designed attics with ventilations at the eaves are not moisture safe, neither are the ones with reduced ventilation with gable ventilation openings. However, the risk becomes lower further north in Sweden.
- Insulation of the roof improves the moisture conditions of the attic. However, the risk levels are determined by the location in the country and the orientation of the building.
- Controlled ventilation represents a robust technical solution, which can withstand the spread in workmanship (airtightness) and moisture supply as well as future climate.
- Controlled ventilation represents the most cost effective alternative.

- A revised drying potential represents a promising new indicator for the moisture safety of ventilated structures such as attics for evaluation and comparison of alternative designs, locations and orientation, including estimates for future climates.

Acknowledgements

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Prediction of indoor climate based on questionnaires

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KEYWORDS: *indoor climate, relative humidity, indoor temperature, air tightness, questionnaire*

SUMMARY:
The main goal of our study was the validation of a formerly presented model to calculate the indoor humidity. Indoor humidity is the most important boundary condition for the hygrothermal behaviour of building components. With the presented model, the durability and life-cycle costs of building components can be predicted. The presented work forms the basis for decision making during the design process.

In this study, questionnaires from 38 households were collected regarding indoor moisture production and ventilation behaviour. The questionnaire answers and values from literature were used as inputs in the formerly presented model. Temperature, relative humidity, and air tightness measurements were performed in parallel. The outcome was compared to the calculation results and used to validate and refine the model.

The calculated results fit well to the measured values, if the humidity is in the low to average range. When absolute indoor humidity is very high, the calculation shows variance from the measured values. The calculated maximum is 15 g/m³, which exceeds the measured maximum of 11 g/m³. Theories for the variance have been postulated; however, specific questions for airtight buildings should be included in future questionnaires to determine the reasons for the variance.

The work forms part of the Austrian contribution to IEA Annex 55.

1. Introduction

Different aspects must be considered during the building design process. Cost minimization, durability (over the building's lifespan) and high energy efficiency are three typical performance goals, which can result in different design solutions. The most important aspects for durability are indoor and outdoor climate and the fault tolerance of the construction.

This study focuses on the prediction of indoor climate, which is the first step in the formerly presented probabilistic model to calculate life-cycle costs (Harreither et al. 2012). Values for moisture production in residential buildings were published by Kalamees et al. (2006), Hartmann et al. (2009) and Geving & Holme (2011). Even standardized values can be found (DIN Fachbericht 2010). In this study, daily production rates in homes were calculated based on the above literature values and applied to the data from the questionnaires. Values to quantify the ventilation rates by window opening were taken from Reiß & Erhorn (2009). The ventilation rates by infiltration or a mechanical ventilation system were taken from standards. Monthly mean values were calculated in this study, which will form the basis to calculate the building components lifespans.

2. Investigation

Two housing projects were investigated during winter 2012/2013 in Vienna and summarized in this study.

PSG is a low-rise high-density housing project on the east side of Vienna and is the first project in our study. Questionnaires were distributed to all 91 households in November 2012. By the end of January, we received 39 completed questionnaires, performed 34 Blower-Door tests and measured temperature and relative humidity in 28 houses.

The second project is KW, a multi-storey residential apartment building on the north side of Vienna. Ten flats took part in our study by completing questionnaires and joining the temperature and relative humidity measurements during January 2013.

2.1 Investigated houses in PSG-project

The PSG housing project is described in detail in Zingerle (2013). 91 nearly identical detached houses were built within a social housing project in 2009. All houses have two floors with 52 m² gross floor area (GFA). Each house has dimensions of 4.75 m x 11.00 m. The net floor area is 84 m². Most of the houses have cellars too. Half of the houses are orientated east-west and the other half are orientated north-south.

The houses consist of timber frame walls and a timber frame roof. The ground floor slab and the cellars are composed of reinforced concrete. The exterior wall assembly on the ground floor is gypsum board, OSB, vapour barrier, timber platform framing with thermal insulation and an ETICS on the exterior. The exterior walls on the upper floor have wooden cross-battens and a ventilated curtain-wall facing instead of the ETICS. The timber frame roof is composed of gypsum board, battening, a vapour barrier, wooden beams with thermal insulation, wooden planking, a ventilation layer, wooden planking, and an EPDM foil on the exterior.

None of the houses in PSG have a balanced mechanical ventilation system, but all the houses have fans in the toilet on the ground floor and in the upper floor bathroom. The toilets on the ground floor are windowless but the bathrooms on the upper floor have two windows on opposite walls with dimensions 2 m x 1 m.

We equipped 28 houses in PSG in January 2013 with two data loggers each. One logger was mounted on the ground floor in the middle of the open plan kitchen/dining/living rooms at head height. On the upper floor, the loggers were placed in the bedrooms. When it was not possible to place the data logger in the bedroom, the loggers were placed in another upper floor room (nursery or study). Most inhabitants state that the internal doors are always open, so it was assumed that the upstairs was also hygrothermally coupled.

Blower-door-tests were also conducted in these 28 houses and six other houses.

2.2 Investigated flats in KW-project

An apartment building with 45 flats was built in 2009 as a social housing project. The GFA of the five-storey building is 5300 m² and the investigated flats have 55 - 110 m² net floor area. There are one storey flats and two storey maisonettes. Four of the investigated flats have bathrooms with a window; the other bathrooms have no window. A centralized balanced mechanical ventilation system is provided for all flats.

The external walls are made of reinforced concrete with ETICS on the exterior and plaster finish on the interior. The flat concrete roof has external thermal insulation. The external covering is either gravel or green roof. The interior partitions are either made of concrete or insulated stud walls with gypsum board.

Temperature and relative humidity loggers were placed in the living room and bedrooms of each investigated flat.