Mold in dwellings: field studies in a moderate climate

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ABSTRACT

Mold in dwellings is a persisting complaint in moderate climates. Nine parameters intervene in it: (1) climate, (2) inside temperature, (3) vapor release, (4) ventilation, (5) lay out, (6) envelope thermal performance, (7) sorption inside, (8) presence of preferential condensation surfaces and (9) type of finish. Exterior climate acts as boundary condition while inside temperature, vapor release and ventilation belong to the living habits. The five others are design and construction related.

Several mold cases have been reanalyzed with as major objective to evaluate if the nine parameters explained the problem. The answer is yes. Especially lack of ventilation, large surfaces of exterior walling, low inside temperatures and poor envelope thermal performance rank high. A low inside temperature anyhow is typically the result of a rebound effect, the fact that the dwelling has such poor thermal performance that people accept lower comfort to keep heating payable. Ventilation in turn is to a large extent building-related. In most cases, no intentional ventilation system is provided. In insulated dwellings, thermal bridging is the main cause. If there is an impact of sorption, preferential condensation surfaces and type of finish could not be confirmed.

INTRODUCTION

Mold in dwellings is a persisting complaint in moderate climates (Hens, 1999), with buildings loosing part of their market value. Inhabitants feel distressed. The mycotoxines molds produce impact health. Especially people with dust allergy are sensitive. Spores of Stachybotris and Aspergillus Fumigatus are quite dangerous when inhaled in large quantity (ASHRAE, 2001). In timber framed buildings, mold mainly develops on studs, plates and sheathing inside the walls. In stony construction mold grows on inside surfaces.

THE THEORY REVIEWED

Mold needs appropriate temperatures, moisture, oxygen, light and nutrients to germinate and grow (IEA-Annex 14, 1990, Adan, 1994, Sedlbauer, 2001). In buildings, moisture is the restricting condition. Mold has been intensively studied on agar, resulting in mold specific isopleths which correlate growth rate to temperature and water activity. Of all molds diagnosed on internal surfaces, Aspergillus Versicolor has the lowest isopleth (representing the slowest growth rate, ending in visible mold after a considerable period of time). That isopleth is well matched by:

$$\phi_{threshold} = 0.00033\theta^2 - 0.015\theta + 0.96 \qquad \text{Eqn 1}$$

As agar is a richer substrate than building and finishing materials, the equation has been condensed in a monthly mean 80% threshold. For shorter periods, a logarithmic function is used (t in days):

$$\phi_{threshold} = \min\{1,\ 0.8\,[1.25 - 0.075\ln(t)]\} \qquad \text{Eqn 2}$$

indicating that mold may develop faster, on condition that the period-mean relative humidity surpasses 80%. Xerophilic molds anyhow do not like 100%. Monthly means may be treated as steady state. In such case and on condition that the room air is mixed uniformly, the relative humidity at a surface is given by the ratio between the room water vapor and the surface saturation pressure. That simple condition links all mold defining parameters, except sorption and type of finish:

Vapor balance

$$p_i = \frac{6.2110^{-6}\left[G_{a,ei}p_e + \sum\left(G_{a,ji}p_j\right)\right] + G_{v,P} + \beta A_{cond}p_{sat,cond}}{6.2110^{-6}\left[G_{a,ie} + \sum G_{a,ij}\right] + \beta A_{cond}}$$

Critical surface temperature ratio

$$p_{sat} = \frac{p_i}{0.8}, \quad f_{h_i} = \frac{\theta_{si}\left(p_{sat}\right) - \theta_e}{\theta_i - \theta_e}$$

Eqn3,4

with G_a the air flow in kg/s, $_e$ exterior, $_j$ adjacent room, $_i$ the room considered (ij: from room i to room j), θ temperature, f_{hi} temperature ratio, p vapor pressure in Pa, $p_{sat,cond}$ saturation pressure in Pa at and A_{cond} area where condensation develops in m², β the surface film coefficient for diffusion in s/m and G_{vP} vapor release or vapor sink in kg/s (all means). Figure 1 illustrates the formulas for a situation where 0 or 25.3 kg air per hour enters a sleeping room from the bathroom. The sleeping room has also outside air ventilation. Vapor production in the bathroom is 1200 g/day, in the sleeping room 800 g/day. Temperatures: 24°C, respectively 16°C. The sleeping room has 2 m² of single glass or better.

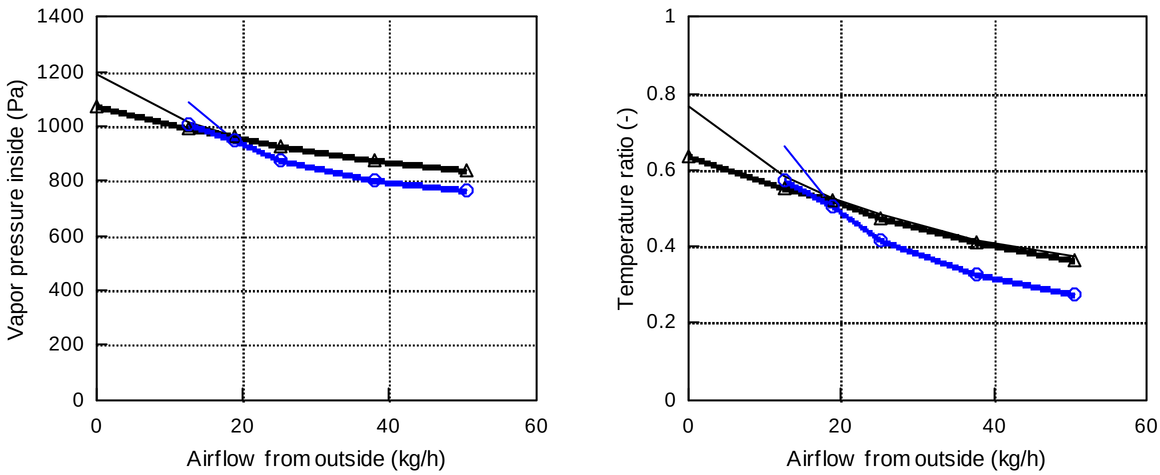

Figure 1 Sleeping room in series with a bathroom, inside vapor pressure and critical temperature ratio during the month of January (θ=2.7°C, p=663 Pa). Black gives the results with inflow from the bathroom, blue without. The thick lines stays for 2 m² of single glass in the sleeping room, the thin lines for double glass and better.

PRACTICE CASES

Thirty three mold cases have been reassessed and the results condensed in the matrix below (Laboratory of Building Physics, 1972-2002). Columns 4 to 8 contain information on:

(2). Inside temperature. N for normal (±21°C), L for low (less than 18°C). The first line for the daytime rooms, the second for sleeping rooms

(3). Vapor release inside (N for normal, H for high)

(4). Ventilation system (V if yes, nV if not), ventilation by window use (Y if done, N if not)

(5). Lay out of the room. 1, 2, 3 refers to the number of exterior walls

(6). Envelope thermal performance. N indicates no or a very modest insulation (for example: walls or roofs only), Y indicates insulation. TB indicates thermal bridges.

(7). Glazing (S for single, D for double, D+ for better than double). Strips means window frames air-tightened

In all cases outside temperature and relative humidity were typical for a moderate, humid climate with a long-term annual mean of 9.5°C, 84.5% RH and annual amplitude of 6.9°C, 7.1%. If not indicated otherwise, buildings have brick cavity walls with floors, lintels, columns and beams in concrete.

Nr	Year	Case	(2)	(3)	(4)	(5)	(6)	(7)
1	1972	Apartment building, concrete skeleton. Mold in 2D and 3D exterior corners. Moisture ratio wall paper: 11% (RH>80%). Mean RH_i 59% mean temperature: 20°C	N	N	nV Y	4	N, TB	S
2	1974	Detached house. Mold on exterior walls and in 3D exterior corners between exterior walls, floor and ceiling in bathroom and toilet. RH in bathroom between 45 and 59%, peaks to 72%.	N	N	nV Y	3	N, TB	S
3	1975	Low income estate. Mold in 2D exterior corners in bathroom, mold behind cupboard and in 3D corners in sleeping rooms	N, L (bathr.)	N	V Y	3	N, TB	S
4	1975	Low income estate. Mold and surface condensation in bathroom and toilet	N, L (toilet)	N	nV Y	2, 3	N, TB	S
5*	1978	Detached house. Mold behind cupboard and around windows in the parents sleeping room , mold in a 3D exterior corner.	L	N	nV Y	4	N, TB	S
6*	1978	Detached house. Timber framed. Mold at the ceiling, along an outside wall	N, L	N	nV Y	2	Y, TB (bad work!)	D
7	1979	Apartment building. Mold in the 2D exterior corners in all rooms, mold on lintels and around windows	N, L	N	nV N (window airtight)	2, 3	Y, TB	D
8	1980	Tobacco factory, air conditioned Mold and surface condensation on the exterior walls	N	H	V Y	1	N, TB	S
9*	1981	Detached house, timber framed. Mold in living and sleeping room	N L	N	nV N	1, 2	Y	D Strips
10*	1981	Detached house. Cellular concrete construction. Severe mold problems in most rooms.	N L	H (built in moist.)	nV Y	1,2,3	Y, TB	D
11	1982	Apartment building. Mold on lintels and in 2D-corners at the highest floor.	N	H (rain penetration)	nV Y	2,3	Y, TB	D
12*	1982	Detached house. Insulated during retrofit. Mold on the lower part of the exterior walls, mold in corners and on furniture	N L	H (rain penetration)	nV N	2, 3	Y, TB	D+
13*	1982	Detached house. Mold in the cupboard in the living and the parents sleeping room). Condensation on double glass	L	N	nV Y	2, 3	N	D Strips
14*	1982	Apartment building. Concrete skeleton with fill-in walls. Mold on the columns and beams in the exterior walls	N	N	nV Y	2, 3	Y, TB	D
15	1982	Detached house. Mold and surface condensation	N L	N	nV N	2, 3	Y, TB	D
16*	1983	Detached house. Mold on concrete beam, mold in 3D exterior corners, mold around windows	N L	N	V Y	2, 3	Y, TB	D Strips

Nr	Year	Case	(2)	(3)	(4)	(5)	(6)	(7)
17	1984	Low income estate. Mold on the ceiling of the second floor sleeping rooms, mold in 3D exterior corners, mold on edge beams	N L	N	nV Y	2, 3	N, TB	D Strips
18	1987	Large apartment building, massive construction. Severe mold on lintels and around window	N L	N	nV Y	2, 3	N, TB	S
19	1987	Detached house (physician) Mold in the waiting room on lintel and around window. Surface condensation against the ceiling along the window in the parents room	N L	N to H	nV Y	2, 3	Y, TB	D Strips
20	1988	Low income estate. Mold in 3D-exterior corner in sleeping rooms	N	N	V Y	2, 3	N, TB	S Strips
21* TR n_{50}	1988	Low income estate. Dwellings retrofitted. Severe mold on exterior walls, lintels and sleeping room ceiling	N L	N	nV N	1, 2, 3	N, TB	D Strips
22*	1992	Detached house. Spreaded mold. Leaks between living room and crawl space.	N L	H	nV Y	1, 2, 3	Y	S
23*	1992	Detached house. Mold on outside wall in living and in sleeping room. Wall in sleeping room insulated inside	N L	N	nV N	1, 2, 3	Y, TB by thermal looping	D Strips
24*	1993	Apartment building. Concrete skeleton. Mold on the beams and columns in the outside walls	N	N	nV N	1, 2, 3	N, TB	S Strips
25	1993	Detached house. Severe mold on the ceiling	L	N	nV N	1, 2, 3	N, TB	D Strips
26*	1993	Detached house. Mold in the living room underneath the exterior wall, mold in 3D exterior corners in sleeping rooms and bathroom	N L	N	nV N	1, 2, 3	N, TB	D Strips
27* TR n_{50}	1994	Apartment building. Severe mold and surface condensation in a 2D-exterior corner of a sleeping room. Mold on the ceiling allover the flat.	N N	N	nV N	1, 2, 3	N, TB	D Strips
28	1996	Office building, double skin façade. Condensation in the facade	N	N	V (HVAC)	1, 2	DsF	D+ Leaky
29* TR n_{50}	1996	Detached house. Severe mold in sleeping rooms, mold on exterior walls and wall between sleeping rooms and garage. Mold in living room below cupboard	N N	N	nV Y	3, 4	Y, TB Bad workmanship	D Strips
30	1997	Apartment building. Spread problems with mold	N	N	nV Y	1, 2, 3	N, TB	S Metal windows
31* TR	1998	Industrial storage, Severe surface condensation, mold on some of the stored goods	L	H	nV N	5	Y	None
32* TR n_{50}	1999	Apartment building. Concrete skeleton. Mold on concrete columns in outside walls in 10% of all flats	N L	N	V Y/N Fuses removed	1, 2, 3	Y, TB	D Strips
33* TR n_{50}	2001	Low income estate. Mold in the sleeping rooms in horizontal 2D and 3D exterior corners, mold around the windows	N	N	nV Y	2, 3	Y, TB	D Strips

Inside temperature, inside relative humidity and inside vapor pressure excess were measured in the 17 cases with asterix. Figure 2 compares the weekly average with the indoor climate class thresholds as used in Belgium. The dashed line gives the limit between indoor climate class 3 and 4 for Ukkel, Belgium, as proposed by Annex 24 (Sanders, 1996). Apparently, moldy residential buildings are not excessively humid. Of the 17 cases measured, only 12, 21, 23, 24, 26 and 27 belong to ICC 4, building with high indoor humidity. Case 12 struggles with rain penetration, while the cases 21, 23, 24, 26 and 27 are all too air-tight for adventitious ventilation.

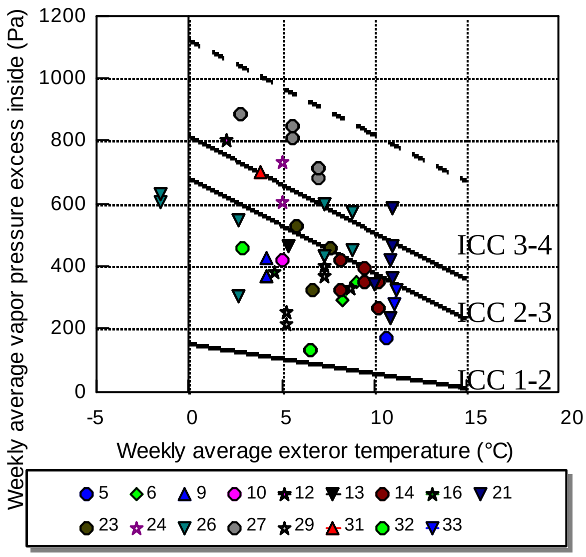

Figure 2 Weekly mean inside vapor pressure excess as function of weekly mean exterior temperature. The numbers refer to the case in the matrix

We also calculated the temperature ratio needed too prevent mold from developing, using the monthly mean threshold of 80%. Figure 3 summarizes the result. One point passes a ratio 1. Reason: the very high relative humidity inside in that case. The figure underlines that a temperature ratio 0.7, a value advocated as an acceptable 5% risk reference, may not be as safe as supposed. In fact, in twelve cases a value higher than 0.7 is needed to prevent mold from developing. However each case could be explained. Ten concern bedrooms. In moderate, humid climates, bedrooms are poorly heated which leads to a high relative humidity inside (Sanders, 1996). In case 5 a cupboard was fixed against the outside walls hindering heat exchange with the room. Case 12 suffered from rain penetration. The cases 9, 16, 21, 23, 24, 27, and 32 showed insufficient ventilation (building too airtight). We should therefore handle the 0.7 temperature ratio not as a stand-alone assurance but add four requirements: ventilation guaranteeing good IAQ, only vapor produced inside as moisture source, enough heating, U-values low enough to give a temperature ratio 0.7 behind cupboards. Also, quite clear from the matrix, we practically always look to rooms with 2, 3 or 4 exterior walls. This lowers the radiant heat exchange between surfaces.

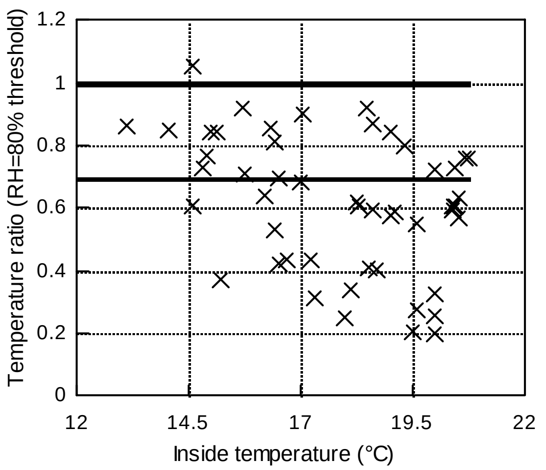

Figure 3 Temperature ratio for the RH=80% threshold.

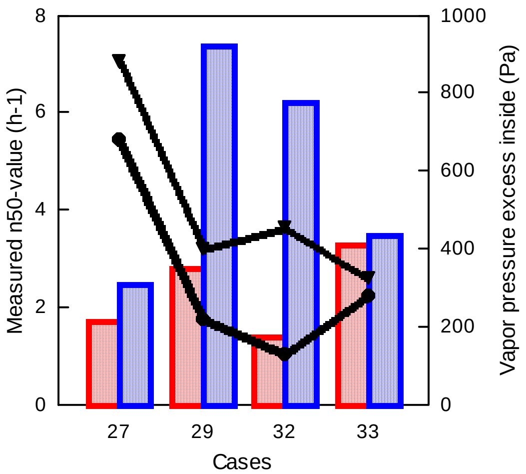

Figure 4 n_{50}-values. Red bars for ventilation grids sealed, blue bars for ventilation grids open. The black lines give the mi-nimum and maximum weekly mean vapor pressure excess inside

Some common opinions are also wrong. A few practitioners and court experts for example still believe that usage of single glass as a preferential condensation plane is an effective measure in minimizing mold risk. This clearly is not true, as the cases 1-5, 8, 20, 22, 24 prove. The drying potential is too low, at least if one likes to keep the glass area within acceptable limits.

TR in column 1 indicates that temperature ratios on thermal bridges were monitored. Values varied between 0.46 (3D exterior corner at floor level) and 0.89 (concrete ceiling in a sleeping room, roof pitches and not the ceiling insulated, pitches air permeable). No mold was found on spots with a temperature ratio >0.7, except in 2 cases of 0.75.

Finally, the air-leakage measurements, n_{50} in column 1, are shown in figure 4. With the ventilation grids sealed, air-leakage in all four cases was too low to assure enough adventitious ventilation. In case 27, opening the few grids (kitchen hood, toilet vent) had no effect. In case 29 it seems as if the grid system is well dimensioned. This is not. Each room got a ceiling outlet but no inlet. In case 32 the apartments were equipped with extract ventilation. Some inhabitants however removed the fuses (fans are somewhat noisy). Case 33 finally had hardly a grid to open! Anyhow, only case 27 reflected air-tightness in the vapor pressure excess measured. Main reason: quite some window use in cases 29 and 33, correct usage of the extract ventilation in most apartments in case 32.

CONCLUSIONS

The mold theory, as developed over the years, is well reflected in the 33 cases analyzed. Main reasons for abundant mold growth in fact are:

– Inside temperature too low, reason why so many sleeping rooms are affected
– Vapor release backed by other sources, as rain penetration and built in moisture
– Unfitted ventilation. New residential buildings too airtight for adventitious ventilation. No designed ventilation system. If present, not used
– A room lay-out with many exterior walls, resulting in low radiant exchanges and leaving no choice where to put cupboards. Against outside walls!
– Overall bad envelope thermal performance before the energy crisis. Since, thermal bridges

The effect of sorption indoors, the presence of preferential condensation surfaces and the type of finish could not be assessed systematically, although it was quite clear that none of them prevented mold from developing. Even single glass could did not do it.

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