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Applied Building Physics

Ambient Conditions, Building Performance and Material Properties

Second Edition

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Preface

Until the first energy crisis of 1973, building physics was a rather dormant field within building engineering, with seemingly limited applicability. While soil mechanics, structural mechanics, building materials, building construction and HVAC were perceived as essential, designers sought advice on room acoustics, moisture tolerance, summer comfort or lighting only when really necesary or when problems arose. Energy was even not a concern, while thermal comfort and indoor environmental quality were presumed to be guaranteed thanks to infiltration, window operation and the heating and cooling system installed. The energy crises of the 1970s, persisting moisture problems, complaints about sick buildings, thermal, visual and olfactory discomfort and the move towards more sustainability changed it all. Societal pressure to diminish energy consumption in buildings without degrading usability activated the notion of performance based design and construction. As a result, today, building physics – and its potential to quantify related performance requirements – is at the forefront of building innovation.

As with all engineering sciences, building physics is orientated towards application, which is why, after the first volume on the fundamentals, this second volume examines performance metrics and requirements as the basis for sound building engineering. Choices have been made, among others to limit the text to the heat, air and moisture performances. Subjects treated are: the outdoor and indoor ambient conditions, the performance concept, performance at the building level, performance metrics at the building enclosure level and the heat-air-moisture material properties of building, insulation and finishing materials. The book reflects 38 years of teaching architectural, building and civil engineers, bolstered by close to 50 years' experience in research and consultancy. Where needed, information from international sources was used, which is why each chapter ends with an extended reading list.

The book uses SI units. Undergraduate and graduate students in architectural and building engineering should benefit, but also mechanical engineers studying HVAC and practising building engineers, who want to refresh their knowledge. The level of discussion presumes that the reader has a sound knowledge of the fundamentals treated in the first volume, along with a background in building materials and building construction.

Acknowledgements

The book reflects the work of many people, not just the author. Therefore, I would like to thank the thousands of students I have had during my 38 years of teaching. They have given me the opportunity to optimize the content. Also, were I not standing on the shoulders of those who precede me, this book would not be what it is. Although I started my career as a structural engineer, my predecessor, Professor Antoine de Grave, planted the seeds that fed my interest in building physics. The late Bob Vos of TNO, the Netherlands, and Helmut Künzel of the Fraunhofer Institut für Bauphysik, Germany, showed the importance of experimental work and field testing for understanding building performance, while Lars Erik Nevander of Lund University, Sweden, taught

that solving problems does not always require complex modelling, mainly because reality in building construction is always much more complex than any model could simulate.

During my four decades at the Laboratory of Building Physics, several researchers and PhD students have been involved. I am very grateful to Gerrit Vermeir, Staf Roels, Dirk Saelens and Hans Janssen, colleagues at the university; also to Jan Carmeliet, professor at the ETH, Zürich; Piet Standaert, principal at Physibel Engineering; Jan Lecompte; Filip Descamps, principal at Daidalos Engineering and part-time professor at the Free University Brussels (VUB); Arnold Janssens, professor at the University of Ghent (UG); Rongjin Zheng, associate professor at Zhejiang University, China; Bert Blocken, full professor at the Technical University Eindhoven (TU/e); Griet Verbeeck, associate professor at the University of Hasselt; and Wout Parys, all of whom contributed through their work. The experiences gained as a structural engineer and building site supervisor at the start of my career, as building assessor over the years, as researcher and operating agent of four Annexes of the IEA, Executive Committee on Energy in Buildings and Communities forced me to rethink my engineering-based performance approach time and again. The many ideas I exchanged and received in Canada and the USA from Kumar Kumaran, the late Paul Fazio, Bill Brown, William B. Rose, Joe Lstiburek and Anton Ten Wolde were also of great help.

Finally, I thank my family, my wife Lieve, who manages to live with a busy engineering professor, my three children who had to live with that busy father and my many grandchildren who do not know that their grandfather is still busy.

Leuven, January 2016 *Hugo S.L.C. Hens*

3.2.9 Bio-germs

3.2.9.1 Viruses

Both a too low and too high relative humidity can have adverse effects on the airborne transmission of viruses. A study by the US National Institute for Occupational Safety and Health showed that the transfer of the influenza virus between coughing and non-coughing people reduced significantly if relative humidity was not permanently below 40%, as is often the case indoors in winter, but rather is kept between 40% and 73%.

3.2.9.2 Bacteria

Legionella pneumophila, a feared bio-germ, can develop in water at 20–40 °C, a temperature range present in air humidifiers, cooling towers, hot water pipes and spray installations. Propagation occurs via water mist in the air. When inhaled by persons with weakened immune system, the germ can cause a deadly lung inflammation known as the legionnaire's disease. For combating the bacterium regularly boosting the domestic hot water temperature to just above 60 °C, cleaning air handling units, disinfecting cooling towers regularly, avoiding stagnant water in long hot water pipes and mixing hot and cold water at the taps suffices.

3.2.9.3 Mould

The micro-fungi called moulds have no leaf green activity, digest their food externally and reproduce by releasing spores. When these deposit on a suitable substrate, their life cycle with germination, mycelium growth, spore formation and spore release starts. The following species typically colonize indoor surfaces (all deuteromycetes):

Species	Percentage of cases (14 studies)
Aspergillus	93
Penicillium	85
Cladosporium	71
Aureobasidium	64
Alternaria	57

The spores float in the air. Surface infestation requires the right conditions: some oxygen, a preferred temperature, carbon, nitrogen and salts in the substrate, and enough humidity. Oxygen below 0.14% m^3/m^3 suffices for germination and growth. The right temperature ranges from 5 to 40 °C. More than minimal amounts of carbon, nitrogen and salts are not needed, but relative humidity is critical. The right value differs between mould families and depends on temperature. Mould-specific isopleths reflect the impact of temperature and relative humidity on growth rate, see Figure 3.13 with two simplified

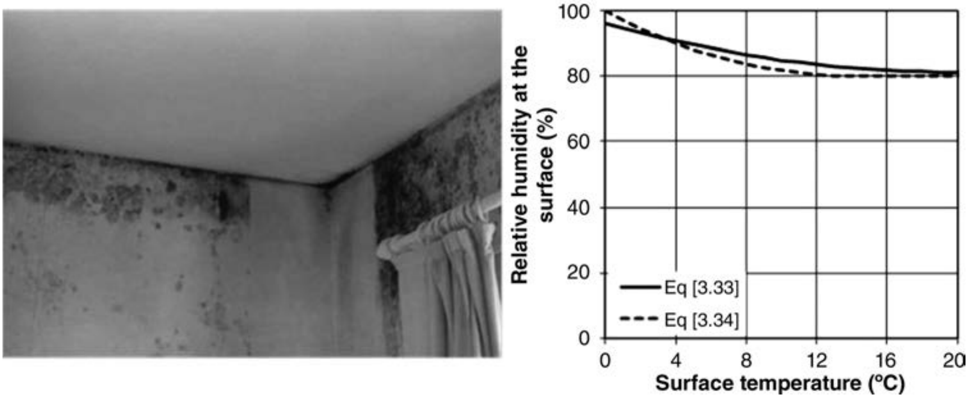

Figure 3.13 Isopleths fixing the lowest mould growth rate.

isopleths drawn that fix the lowest rate:

1) $\phi_{\text{crit}} = 0.033\theta_{\text{s}}^2 - 1.5\theta_{\text{s}} + 96$ (3.33)

2)
$$\begin{aligned} &\theta_{\text{s}} < 20\,^{\circ}\text{C}\ \phi_{\text{crit}} = \max\left(80, -0.00297\theta_{\text{s}}^3 + 0.16\theta_{\text{s}}^2 - 3.13\theta_{\text{s}} + 100\right)\ (\%) \\ &\theta_{\text{s}} \geq 20\,^{\circ}\text{C}\ \phi_{\text{crit}} = 80\% \end{aligned} \tag{3.34}$$

For isopleths nearing the optimal temperature and relative humidity combinations, growth rate increases and the period before germination shortens. Beyond this, growth rate drops again. Globally, at surface temperatures of 17–27 °C, a four-week mean surface relative humidity of 80% (0.8 on a scale from 0 to 1) suffices to see aspergillus, cladosporium and penicillium colonizing substrates with limited nutritive value. This 80% figure has therefore been chosen as the design value for controlling mould risk on inside surfaces. Risk is assumed 1 when the four-week mean vapour pressure on a surface (p_{s}) exceeds 0.8 times the four-week mean saturation value ($p_{\text{sat,s}}$):

$$p_{\text{s}} \geq 0.8 p_{\text{sat,s}} \tag{3.35}$$

Mean relative humidity values beyond 80% shorten the period for germination (t in days):

$$\phi_{\text{crit}} \geq \min\left\{100, \left(0.033\theta_{\text{s}}^2 - 1.5\theta_{\text{s}} + 96\right)[1.25 - 0.072\ln(t)]\right\} \tag{3.36}$$

Of course, moulds other than the three mentioned, such as stachybotrys, may demand a higher surface relative humidity to germinate. In recent decades, investigations have refined the tools available for evaluating mould on substrates. Starting from a mixed species population, Finnish researchers have introduced a growth index to evaluate mould density on pine and spruce:

Index	Growth rate	Description
0	None	Spores not active
1	Small spots of mould on the surface	Initial growth stages
2	Less than 10% of the surface covered	
3	10–30% of the surface covered	New spores produced
4	30–70% of the surface covered	Moderate growth
5	>70% of the surface covered	Considerable growth
6	Very heavy and tight growth	100% coverage

German researchers classified substrates into four classes according to mould sensitivity:

Class	Type
0	Optimal substrate (agar)
1	Biodegradable materials
2	Typical building materials
K	Critical for mould on an optimal substrate

They dealt with mould as an additional layer at the inside, characterized by a mould-specific vapour diffusion resistance, sorption isotherm and growth rate related thickness.

Under the right conditions, moulds grow on any surface, even on the filters in HVAC and ventilation systems that, once infected, contaminate the indoor air with spores more than moulded surfaces do. But they also create other annoyances. Aesthetics are spoiled and economic loss can be caused. In fact, before selling their property, people tend to clean infected surfaces, otherwise the market value of the building would drop. Moulds also upset dwellers and, though not convincingly proven, harm health. Some assume that the mycotoxines emitted aggravate house dust allergy, while exposure to very high concentrations could impair the immune system. However, according to the John Hopkins School of Medicine, the relation between mould on inside surfaces and allergies of the upper bronchi is not substantiated, while the literature on health effects is more agitational than scientific. What is proven is that, at high concentrations, spores of aspergillus fumigatus can colonize the lungs, causing an illness called aspergillosis. Tests on laboratory animals showed that spores of stachybotrys are so toxic that inhaling high concentrations can cause a deadly lung disease called IDH. At low concentrations, however, the white blood cells eliminated the spores. And, the likelihood of encountering spore concentrations in buildings as high as those during the tests is close to zero.

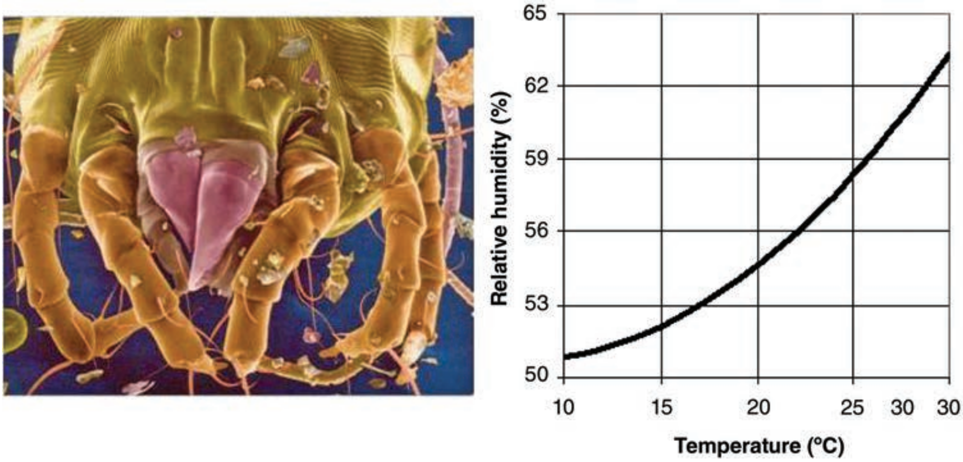

Figure 3.14 Critical relative humidity for the dust mite dermatophagoides farinae.

3.2.9.4 Dust mites

Dust mites are colourless, 0.5 mm long octopods that colonize carpets, textiles, cushions and beds and that feed on human and animal hair and scales. There are 46 different known species with 13 of them found in buildings, and three being found worldwide. Dust mites don't drink. Respiration and perspiration happens through the skin of the back, abdomen and legs. In this way, their moisture balance depends on temperature and relative humidity in their direct environment. The range of 10–30 °C is preferred, though relative humidity for dehydration differs between species. For dermatophagoides farinae the value is:

$$\phi_{\text{crit}} = 52.1 - 0.375\theta + 0.025\theta^2 \tag{3.37}$$

Above the curve shown in Figure 3.14, though depending on temperature, the growth from egg to mature mite accelerates substantially, from 122.8 ± 14.5 days at 16 °C to 15 ± 2 days at 35 °C. For other species the critical relative humidity scatters around 65%.

Dust mite density relates directly to house dust allergy that affects some 20% of the population. Risk analysis in Denmark showed that exposure to the digestive enzymes in mite excrements, suspended in the air, explained up to 60% of the asthma cases. The risk of developing hypersensitivity starts at a concentration of 2 μg per gram of house dust. In order for a sensitive person to get allergic attacks, it has to exceed 10 μg per gram.

3.2.9.5 Insects

The presence of insects indicates spots in buildings showing elevated humidity. Mosquitoes breed and hibernate in moist crawl spaces. Moving into the building

Table 3.9 Mean skull width of rodents and insectivores.

Species	Skull width mm
Common pipistrelle (protected)	7–8
Shrew mouse	9–10
House mouse	10–12
Black rat	16–22
Brown rat	17–27
Hedgehog (protected)	28–38

from there is no problem given the many leaks around pipes in the ground floor. At night the bloodthirsty females come out and attack the sleeping human victims. Humid cavities behind baseboards and rotting timber sills shelter cockroaches, fleas and other insects. In buildings with air heating, cockroaches sometimes become a real nuisance as they nestle in the air ducts. Atopic people react allergically to certain enzymes in their excrement, which the warm supply air ejects. Extermination of insects requires pesticides. Often inhabitants use spray cans, thus allowing the pesticide to pollute the indoor air.

3.2.9.6 Rodents

Due to the damage they cause, rodents are not welcome in buildings. Blood-diluting products are popular in combating them. A better method is preventing entrance by sealing all openings wider than their skull, see Table 3.9.

3.2.9.7 Pets

Cats release substances that provoke allergic and asthmatic reactions in atopic people. An investigation in 93 office buildings in the USA showed that nearly all dust on the floor contained cat allergens although hardly any cats ever entered the buildings. The average concentration sampled was $0.3\,\mu g/g$, the maximum $19\,\mu g/g$. Developing hypersensitivity starts at $8\,\mu g/g$, a value exceeded in 7 of the 93 buildings. The source proved to be the dust coming from the clothes that the employees wore from home, where they had a cat.

3.2.10 Human related contaminants

Humans also contaminate their environment. They pick up oxygen when inhaling and emit carbon dioxide and water vapour when exhaling. Perspiration and transpiration increases water vapour release, while bio-odours out-gas through the skin and are freed by respiration and flatulence. After the (re)discovery of America and the tobacco plant, people started smoking, first in Europe, later worldwide.

3.2.10.1 Carbon dioxide (CO_2)

Healthy humans inhale 4 M litres of air per hour with M their metabolism in watts. The lungs pick up some 27% of the oxygen in the inhaled air and add 4% m^3/m^3 of CO_2. This way, inhaled and exhaled air consists of the following:

	Inhaled air, % m^3/m^3	Exhaled air, %m^3/m^3
Oxygen	20.9	15.3
Nitrogen	79.6	74.5
Carbon dioxide	0.04	4.0
Water vapour	?	6.2

Individuals therefore emit 0.16 M norm-litres of carbon dioxide per hour (M in W). Until a concentration of 50 000 ppm, CO_2 is not considered poisonous, although recent research, albeit disputed, has shown that indoor air concentrations above 1000 ppm could have some effect on intellectual activity. Experiments with 22 subjects subjected to low (600 ppm), medium (1000 ppm) and high (2500 ppm) CO_2-concentrations for 2½ hours in fact showed some reductions in decision-making performance, see Table 3.10. Concentrations nearing 5000 ppm lessen attention even more and initiate drowsiness. Above 10 000 ppm drowsiness reigns, and beyond 40 000 ppm people start complaining of headaches.

3.2.10.2 Water vapour

Water vapour is not a contaminant as such. Its presence, however, activates (S)VOC outgassing and favours bio-germs. At normal activity, humans release less than 40–60 grams of water vapour per hour, though emissions increase proportionally to metabolism (see Figure 3.15).

3.2.10.3 Bio-odours

Bio-odours such as isoprene and 2-propanone are VOCs. Their release is most easily sensed when entering a badly ventilated room having been occupied shortly before by a group of people. It smells 'stuffy'.

Table 3.10 CO_2 impact on human decision-making performance.

Classes	Basic activity	Applied activity	Focused activity	Task orientation	Initiative	Information orientation	Information utilization	Breadth of approach	Basic strategy
Superior	O								
Very good	X	O,X	O,X,Y	O, X		O,X,Y			
Average		Y		Y	O,X		O,X	O,X	O,X
Marginal	Y						Y	Y	
Dysfunctional					Y				Y

O 600 ppm; X 1000 ppm; Y 2500 ppm.

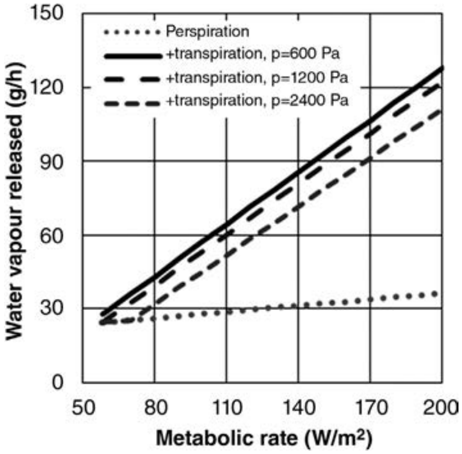

Figure 3.15 Water vapour released by people.

3.2.10.4 Tobacco smoke

Slowly burning hydrocarbons is very efficient. The reaction with oxygen produces carbon dioxide and water vapour. Tobacco, however, contains such a complex set of compounds that even slow burning emits an amalgam of airborne contaminants with nicotine as the habituating substance, see Table 3.11. At the same time, smoking figures as a source of obvious olfactory irritation.

The primary contaminant flow consists of the smoke inhaled by the smoker, the secondary one being the smoke released by the burning cigarette. An active smoker is exposed to a mixture of both, whereas the passive smoker inhales a mixture of secondary and exhaled primary flow. A considerable amount of the primary contaminants remains in the respiratory tract of the active smoker. They are therefore most exposed to the health risks that smoking induces. Although the mixture of exhaled primary and secondary flow is different, in the long run passive smokers are also exposed to analogous health risks. Researchers at the US Department of Energy's Lawrence Berkeley National Laboratory proved that third-hand smoke formed by the reaction of nicotine with indoor nitrous acid and ozone and giving potentially harmful ultrafine particles continues to have impacts for many hours after cigarettes are extinguished. In the tests, more than 50 VOCs and airborne particles were still present 18 hours after smoking took place. Up to 60% of the potential noxious effects remained up to two hours after smoking had stopped.

For chain-smokers, health risks include heart and vascular disease, pulmonary complaints, stomach complaints and lung cancer. Smoking more than one packet of cigarettes a day increases premature death occurrence with 15%, meaning that 1 in 6 chain smokers die because of their habit. For passive smokers it's 1 in 60. To avoid health problems for their child, pregnant women are firmly discouraged from smoking.

Table 3.11 Airborne contaminants in tobacco smoke.

Contaminant	Concentration mg per cigarette	MAC ppm
NO_X	1.801	
NO	1.647	
NO_2	0.198	
CO	55.10	50
Ammoniac	4.148	25
Acetaldehyde	2.500	100
Formaldehyde	1.330	
Acetone	1.229	1000
Acetonitrile	1.145	
Benzene	0.280	
Toluene	0.498	
Xylene	0.297	
Styrene	0.094	
Isoprene	6.158	
1.3 Butadiene	0.372	5000
Limonene	1.585	
Nicotine	0.218	
Pyridine	0.569	
Dust	13.67	
Hydrogen cyanide	1600 ppm	10
Methyl chloride	1200 ppm	100

3.2.11 Perceived indoor air quality

3.2.11.1 Odour

People typically judge the indoor air quality by smelling. Yet, evaluating malodour objectively is a difficult task, which is why at the end of the 1980s P.O. Fanger proposed a perception-based methodology, called the olf/decipol rationale, a source and field model with a human panel as reference instrument. The olf figures as emission unit with a value 1 representing the bio-odours emitted by an adult male with a body area of 1.8 m^2, who is lightly active, takes a shower five times a week, puts on fresh underwear every day and uses deodorant moderately. The decipol (dP) in turn represents odour intensity, where 1 decipol characterizes the olfactory pollution a 1 olf male causes in a room aired with 36 m^3 of zero olf fresh air per hour.

A human panel of ten individuals is trained to quantify decipol values. They first learn to estimate the scale using reference sources. Once trained, they can estimate malodours in spaces during a short visit. The average of the decipols noted by the members represents the perceived value. With the ventilation flow known, this value allows the olfs present to be calculated. In fact, if dP_e is the decipol value outdoors, dP_i the value indoors, n the ventilation rate in ach and V the air volume in the space in m^3, the number of olfs equals:

$$P_{olf} = (dP_i - dP_e)nV/36 \tag{3.38}$$

In most cases, more olfs are noted than people present. These come from out-gassing materials and poorly maintained ventilation systems. The investigations helped weighting sources:

Source	Olf
Reference person	1
Active person, 4 met	5
Active person, 6 met	11
Smoker with cigarette	25
Smoker without cigarette	6
Materials and ventilation systems	0–0.4 olf/m^2

The many panel visits resulted in a statistical relation between perceived malodour in decipol (dP_i) and the number of dissatisfied (PD, %, Figure 3.16):

$$dP_i = 112[\ln(PD) - 5.98]^{-4} \tag{3.39}$$

ASHRAE quotes 20% dissatisfied as acceptable, fixing 1.4 dP as the limit for perceived malodour. In 'sick buildings' the value may be more than 10 dP.

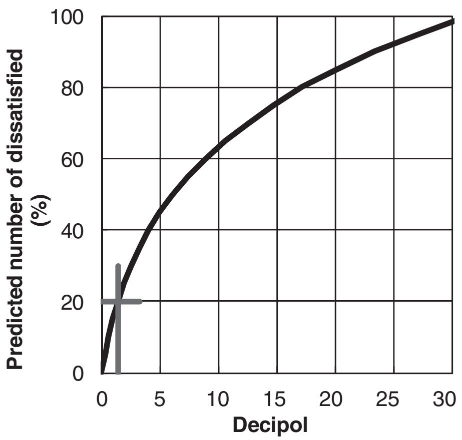

Figure 3.16 The predicted number of dissatisfied (PD) versus decipol relation.

The olf/decipol model is criticized. Using a human odour panel as a measuring instrument induces random doubts about the decipol values perceived, while questions such as 'how do you calibrate the decipol sources used for training?' cast a shadow over the method.

3.2.11.2 Indoor air enthalpy

Complaints about bad indoor air quality seem to multiply with increasing air enthalpy (h), per kg of dry air given by:

$$h = 1008\,\theta + x_v(2\,500\,000 + 1840\,\theta) \tag{3.40}$$

with θ the air temperature in °C and x_v the vapour ratio in kg/kg with as link to relative humidity:

$$\phi = \frac{x_v P_{atm}}{p_{sat}(0.621 + x_v)} \quad (0 \le \phi \le 1)$$

where P_{atm} is the atmospheric pressure (≈100 000 Pa) and p_{sat} the vapour saturation pressure at the air temperature in Pa. The random relation between enthalpy and PD as deduced from experiments is:

$$PD = 100\frac{\exp[-0.18 - 5.28(-0.033h + 1.662)]}{1 + \exp[-0.18 - 5.28(-0.033h + 1.662)]} \tag{3.41}$$

Also here, 20% dissatisfied is taken as acceptable. Investigations in classrooms showed that values logged during teaching hours largely exceed that limit, see Figure 3.17. Ventilation with operable windows opened between teaching hours clearly fails in guaranteeing acceptable indoor air quality.

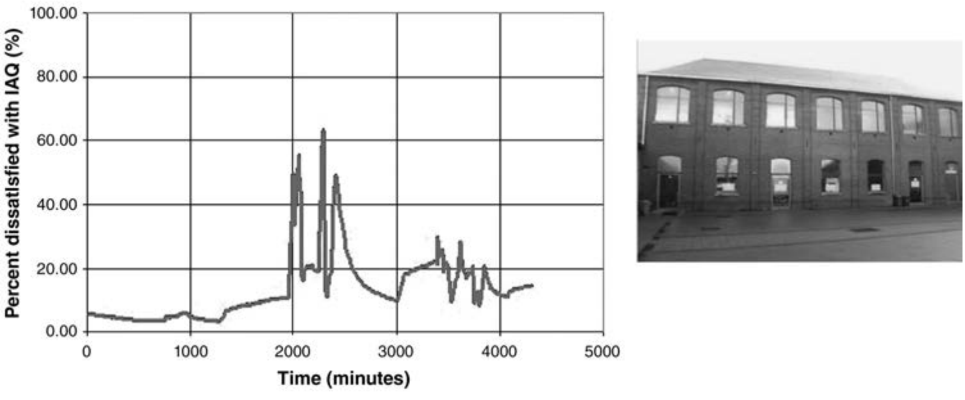

Figure 3.17 Classroom in a secondary school, percentage of dissatisfied with perceived indoor air quality based on measured air enthalpy.

Again, not everyone agrees on the role air enthalpy plays. Some presume it only gains importance when people feel thermally uncomfortable. Individuals then perceive the combination of high air temperature and high relative humidity as oppressive, though lower air temperatures may not stop the complaints. By contrast, a low relative humidity always seems more pleasing.

3.2.12 Sick building syndrome (SBS)

A much-discussed issue linked to bad environmental quality in offices is SBS. In literature, an office building is called sick when contact with outdoors is lacking, space, privacy and quietness fails, visual, acoustical and thermal comfort is questionable and unwanted contaminants pollute the air. Complaints disappear during weekends and holidays but return when work is resumed. Symptoms are eye, nose, sinus and throat irritation, difficulty in breathing, heavy chest, coughing, hacking, headaches and dry skin.

The impact of air quality has been researched intensively, among others by looking to the ventilation system and the magnitude of the ventilation flows, see Figure 3.18. Symptom prevalence at first diminishes but then at higher ventilation rates uncertainty increasingly dominates.

Many studies did not consider other probable causes. Better analyses concluded that fully air conditioned office buildings show 30–200% more SBS complaints than naturally ventilated ones. This is mainly due to dirty ductwork and contaminated filters. Air humidification looked especially guilty. Also the link with the CO_2-concentration has been investigated. Each extra 100 ppm apparently resulted in a 10–30% increase in dry mucous membrane, irritated throat, stuffy nose and coughing complaints.

Another cause of SBS complaints commented on in recent years is work stress. In fact, employees who perform mandated duties complain more than executives. In the cases investigated, the complainants called their job stressful and lacking encouragement. No relation came out with ventilation effectiveness, VOC-concentration or noise level

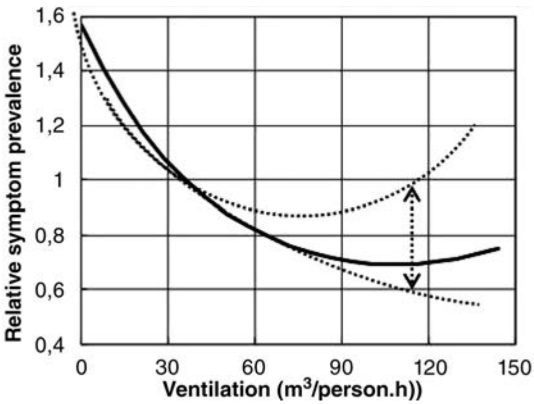

Figure 3.18 Relative symptom prevalence versus better ventilation, mean curve, 95% confidence band (dotted lines).

humidifies neither the thermal insulation nor the layers at its inside, while claddings and veneers that suck rain should suffer neither from detrimental functional nor unacceptable aesthetic degradation.

4.5.3.3 Modelling

During rainy weather horizontal and inclined surfaces always collect water. Vertical surfaces instead only do when rain and wind act together, giving as wind-driven impingement rate:

$$g_{r,v} = (0.2C_r v_w \cos\theta) g_{r,h}$$

θ being the angle between wind direction and normal to the surface. C_r is called the wind driven rain factor, a function of building location, the surroundings, the spot on the facade, local detailing, and so on. The product $0.2C_r v_w \cos\theta$ represents the catch ratio. Its value follows from measurement or calculations combining computerized fluid dynamics (CFD) with droplet tracing. Catch ratios are highest at corners and the top of facades facing the wind, see Figure 4.10 and Table 4.2.

Looking to how to control rain impingement and seepage, the easiest measure is to shield, which is quite efficient and easily done above and along facades by using overhangs. As designers often dislike it for aesthetic reasons, handling drainage, storage and transmission is the other way out (Figure 4.11). Drainage develops along outside surfaces and, where gravity and wind transmit water, between layers in free contact. Buffering becomes a reality when capillary layers suck and retain rain, while transmission happens each time capillary layers contact each other or touch thin air layers that act as drainage planes.

Looking to buffering in more detail, capillary finishes first suck the impinging droplets until their surface becomes capillary saturated. At that stage, a water film forms that adsorption retains for a while until run-off fingers down and wets the areas below, while further buffering until capillary saturation of the finish occurs. How long suction takes

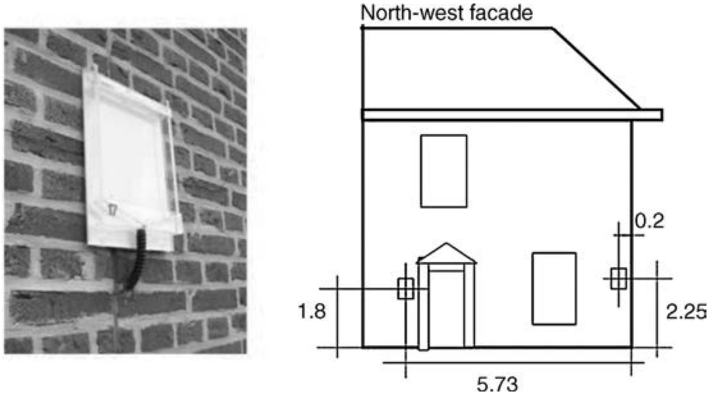

Figure 4.10 End of the row house, north-west facade, wind-driven rain gauges.

Table 4.2 Measured catch ratios, see the house of Figure 4.10.

Location	NW 5.73/1.8 m	NW 0.2/2.25 m	SW 0.36/2.25 m	SW 6.53/1.8 m	NE 1.72/2.25 m	NE 4.38/2.7 m
Catch ratio	0.016	0.26	0.23	0.047	0.008	0.014

(t_f) before run-off begins, depends on the wind driven rain intensity ($g_{r,v}$) and the finish's capillary water absorption coefficient (A):

$$\frac{A}{2g_{r,v}^2} \leq t_f \leq \frac{\pi^2 A}{16 g_{r,v}^2} \tag{4.18}$$

When that coefficient is large and rain intensity low, sucking postpones film formation for quite some time, allowing the layer to buffer lots of rain. When that coefficient is low, film formation proceeds rapidly, quickly turning the outside surface into a drainage plane. Bricks are moderately to highly capillary active ($A = 0.2$–1 kg/(m^2.s$^{0.5}$)). A brick veneer therefore acts as buffering volume, which minimizes the rain load on joints and facade protrusions. Conversely, concrete, concrete blocks, sand-lime stone, water-repellent stuccoes, paints and timber claddings are hardly capillary active ($A \leq 0.02$ kg/(m^2.s$^{0.5}$)). They mainly act as drainage planes. Non-porous materials, such as glass, plastics and metals, give quasi instant run-off.

At first sight, run-off along non-sucking surfaces should give an increased water flow from the zone hit by rain and a constant flow on the non-hit surfaces below. If, as for high-rises, the wetted zone is large, wind driven rain should generate significant run-off, but observation contradicts this. Only the top storeys of high-rises catch rain, while friction, obstruction by facade reliefs and evaporation greatly reduces the run-off on its way down.

As stated, capillary outside finishes act as buffering volumes. However, when in suction contact with a capillary layer behind, rainwater will be transmitted. Gravity intervenes when run-off creates water puddles above facade protrusions or fills leaky joints, which then empty at the rear. Wind does the same by squeezing run-off through cracks wider than 0.5 mm, while the kinetic energy of the impinging droplets supports transmission

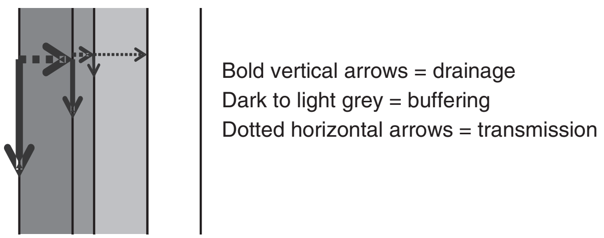

Figure 4.11 Rain control: drainage, storage and transmission.

by pushing run-off through yawning fissures, cracks and joints. Run-off entering a crack or leak seeps through at a rate:

$$G_w = -83.3 b^3 \,\text{grad}\, P_w / \eta \quad (\text{kg/s}) \tag{4.19}$$

with η the dynamic viscosity of water (0.000 15 kg.s/m^2), b the 'equivalent' width and grad P_w the pressure gradient across that crack or leak, gravity-related equal to $\rho_w g z$, with g acceleration by gravity (9.81 m/s^2) and z the depth of the water puddle facing or built up in the crack or leak.

4.5.3.4 Consequences for the building envelope

When designing envelopes, shielding, buffering, exterior surface drainage (one-step control), or combined drainage and buffering with exclusion of unwanted transmission (two-step control) are the measures that, correctly executed, ensure rain-tightness.

The principle behind shielding is simple. What's higher protects what's lower, Take roof overhangs, sills and coping stones (Figure 4.12). Sills require a slope to the outside, a kerf at the underside, end dams and a back dam, principles that help to shape window sashes and frames.

Buffering in turn combines outside drainage with rain storage. To function properly, a buffering wall must be thick enough to keep the moisture away from inside, even after

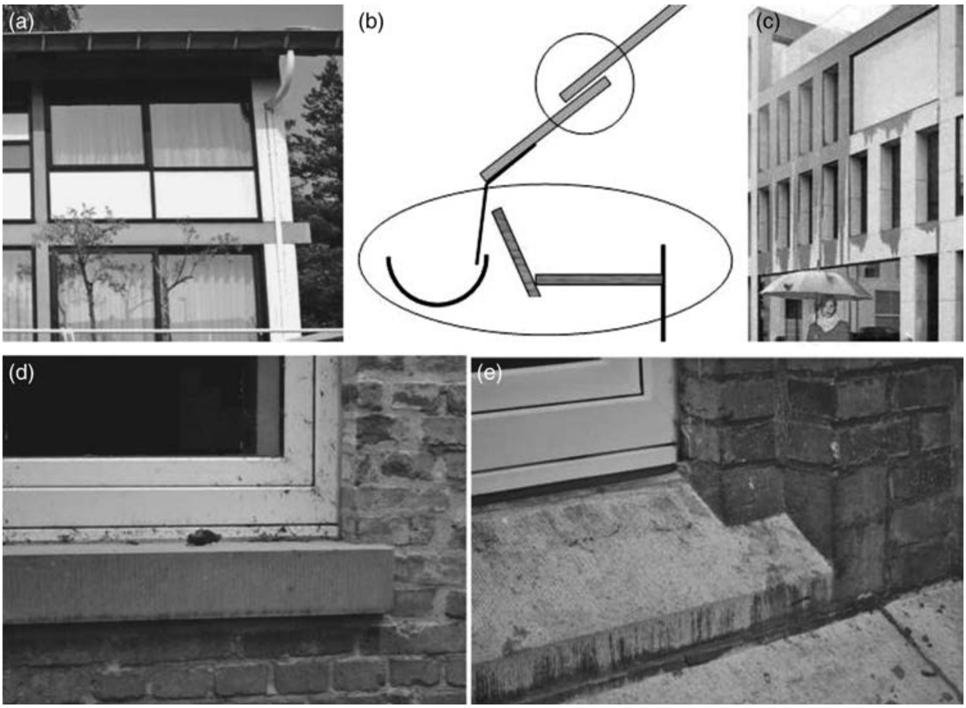

Figure 4.12 (a) and (b) Roof overhang, (c) no overhang and sills, (d) sill without end and back dam, (e) sill with end and back dam.

long-lasting rain events. In temperate but humid climates, 30 hours of uninterrupted rain can happen, whereas 'keep away' means not passing the wall's midline. Take an aerated concrete wall, capillary water absorption coefficient 0.08 kg/(m^2.s$^{0.5}$), capillary moisture content 350 kg/m^3. The thickness needed is:

$$d = 2\left(\frac{A}{w_c}\right)\sqrt{T} = 2\left(\frac{0.08}{350}\right)\sqrt{2.5 \times 24 \times 3600} = 0.21 \text{ m}$$

With masonry, head and bed mortar joints often act as short-circuits, which is why buffering requires one and half brick walls, where-in a continuous mortar joint with air voids that splits the wall in two parts acts as a rain stop, see Figure 4.13. Of course, the bed joints still short-circuit that stop to some extend

In a one step control, the only drainage plane is the outside surface (Figure 4.13). To function properly the outer finish must be watertight, water-repellent or fine-porous. Watertight ones neither buffer nor transmit water. Water repellent ones have a contact angle below 90°, while fine-porous choices must be thick enough to prevent rainwater from reaching the substrate:

$$d_{pl} = B\sqrt{T} \quad \text{(m)} \quad \text{with} \quad B \approx A/w_c$$

where B is the water penetration coefficient and T rain duration. Thin ones thus need a really low capillary water absorption coefficient but a high capillary moisture content, which means very fine pores but high enough porosity and tortuosity. If so, they largely prohibit substrates with wider pores from sucking rain. Of course, fine pores and high tortuosity makes these thin finishes vapour-retarding. A drawback of one-step solutions is damage sensitivity. Once the finish is perforated or cracked, rain can penetrate.

When going for a two-step control, the outside and reverse side of the outer finish act as drainage planes, while a capillary break behind prohibits rain transmission. This could be a cavity or a water repellent thermal insulation. Examples include brick veneers having a tray at the bottom of the cavity behind with weep holes to the outside just above (Figure 4.14), facade elements with open joints and a cavity behind, metal claddings with a cavity behind, and the rebates between hinged window sashes and the frames. The

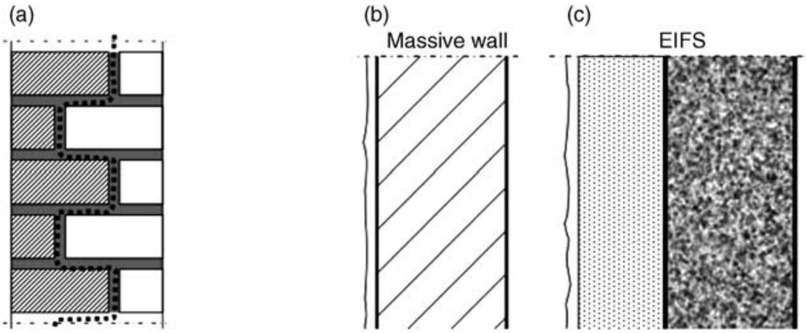

Figure 4.13 (a) rain control by buffering, (b) and (c) one-step control, two examples.

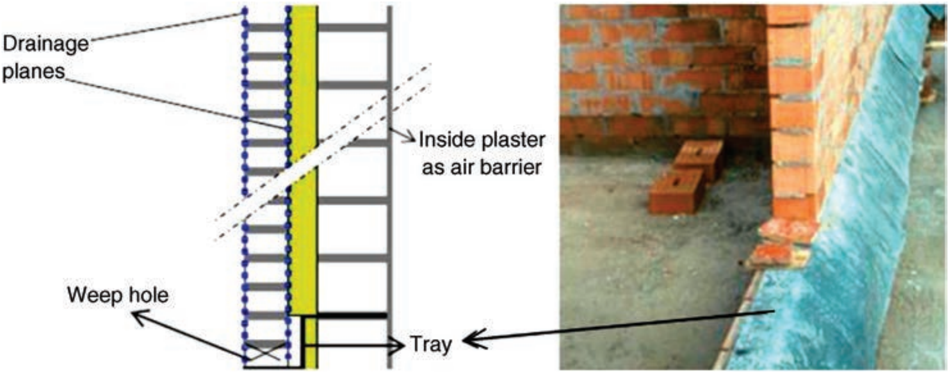

Figure 4.14 Filled cavity wall, two-step rain control.

layers at the inside of the capillary break in turn must be airtight, meaning that rain-tightness and air/wind-tightness are split.

Cavities extending three-dimensionally behind a veneer wall or outside cladding don't level out the wind pressure differences, a necessary condition to avoid heavy wind from blowing reverse side run-off across the cavity to the inside leaf. Compartmentalization of these cavities is often the only way out.

One major advantage of these two step solutions is damage insensitivity. A cracked or perforated outside finish doesn't kill its function. However, professionals often overlook the air and wind barring function of the inside leaf. When closing joints, for example, the best seal, wind- and airtight, should sit on the inside. Many put it outside.

4.5.4 Rising damp

4.5.4.1 Definition

'Rising damp' refers to walls wetted from below, which can happen when a wall or some of its layers are capillary and contact the water table, capillary moist soil, sink water or collected rainwater. This cause of dampness is often seen as a problem that only occurs in massive walls, although also the inside leaf of a cavity wall may suck the veneer's reverse side run-off when the cavity misses a correctly installed tray at the bottom.

4.5.4.2 Performance requirements

Rising damp must be avoided because large areas can become and stay wet, whereas drying to the inside either increases energy use for heating or invokes evaporative cooling, while raising relative humidity indoors and increasing mould risk (see Figure 4.15).

Moisture content in affected walls can reach high values ($w_{cr} \leq w \leq w_c$), resulting in plaster, wallpaper and paint damage. In many cases rising damp carries dissolved salts that crystallize where drying happens. At higher relative humidity they rehydrate. Such

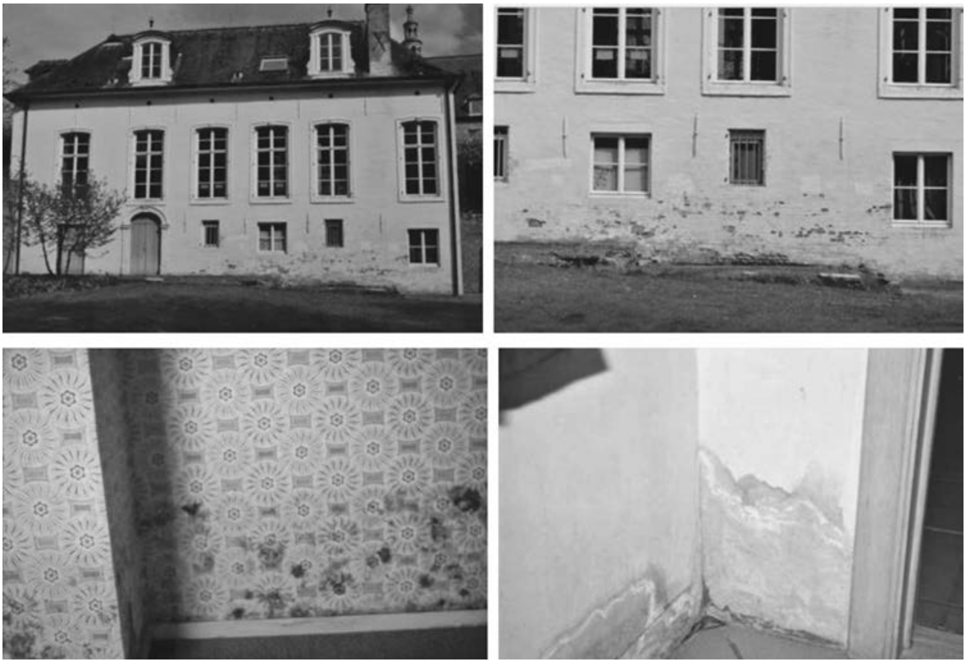

Figure 4.15 Rising damp, causing extensive mould growth.

salts also increase hygroscopicity and retard, even exclude, drying when it is humid and warm outdoors.

4.5.4.3 Modelling

The height at which damp will stop in a homogeneous wall depends on the balance between capillary suction and evaporation at the wall's surfaces. In contact with the water table or with ponding rainwater, rising starts from capillary saturated. When contacting capillary moist soil, the difference in suction between wall material and soil fixes the moisture content to start off. If it is the soil that sucks the most, damp will hardly rise. If it's the wall, then damp will rise but at a lower rate and a lower amount than if in direct contact with water. The ambient conditions at both wall faces and the diffusion resistance of the finishes determine the evaporation. The larger that resistance, the less vapour will evaporate and the higher the damp will rise up the wall for a given suction. A simple model helps clarifying that balance.

In a homogeneous wall, rising per unit of time equals:

$$v_{\mathrm{m}} = r\left(\frac{\sigma \cos \Theta}{4\eta}\right)\left(\frac{1}{h} - \frac{1}{h_{\max}}\right) \tag{4.20}$$

with h the height that is damp and h_{max} the maximum height dampness would reach without evaporation:

$$h_{max} = 2\sigma \cos \Theta / (r \rho_w g)$$

The viscosity (η) and the surface tension (σ) of the rising moisture, the contact angle Θ and the mean radius r of the pores in the material fix the water penetration coefficient as:

$$B = \sqrt{r \frac{\sigma \cos \Theta}{2\eta}} \tag{4.21}$$

or:

$$\frac{B^2}{2} = \frac{r\sigma \cos \Theta}{4\eta}$$

With $B = A/w_c$ and the sucked water flow G_m equal to $v_m w_c d$ with d wall thickness and w_c the material's capillary moisture content, without evaporation the flow and damp height write as:

$$G_m = \frac{ABd}{2}\left(\frac{1}{h} - \frac{1}{h_{max}}\right) \quad h_{max} = \frac{5.5 \times 10^{-4}}{B^2} \tag{4.22}$$

Once at equilibrium, what's sucked must equal what's evaporated (G_e):

$$G_m = G_e = h\left[\frac{p_{sat,1}(1-\phi_1)}{1/\beta_1 + Z_1} + \frac{p_{sat,2}(1-\phi_2)}{1/\beta_2 + Z_2}\right] \tag{4.23}$$

where β_1 and β_2 are the surface film coefficients for diffusion and Z_1 and Z_2 the diffusion resistances of the finishes at both wall faces. Combining both flow equations gives:

$$h^2 - \left[\frac{ABd}{2h_{max}\left(g_{d,1} + g_{d,2}\right)}\right]h + \frac{ABd}{2\left(g_{d,1} + g_{d,2}\right)} = 0$$

a quadratic expression with as positive root:

$$h = \frac{ABd}{4h_{max}\left(g_{d,1} + g_{d,2}\right)}\left[\sqrt{1 + \frac{4h_{max}^2\left(g_{d,1} + g_{d,2}\right)}{ABd}} - 1\right] \tag{4.24}$$

The moisture profile in the wall follows from:

$$\frac{d}{dz}\left(D_w \frac{dw}{dz}\right) = \frac{g_{d,1} + g_{d,2}}{d}$$

If moisture diffusivity (D_w) and the drying rate stay constant along the damp height (h), the solution is ($z=0$: $w=w_c$; $z=h$: $w=w_{cr}$):

$$w=\left(\frac{g_{d,1}+g_{d,2}}{2dD_w}\right)z^2-\left[\frac{w_c-w_{cr}}{h}+\frac{\left(g_{d,1}+g_{d,2}\right)h}{2dD_w}\right]z+w_c \tag{4.25}$$

a parabola with highest moisture content in the contact plane with the water and lowest at final damp height. For a diffusivity that changes with moisture content ($D_w=f(w)$), the profile becomes more rectangular with a smaller gradient along the damp height.

Decreasing moisture content with height is a rising damp characteristic, although dissolved salts can obscure this picture. Figure 4.16 gives the final height in a 30 cm thick, joint free partition wall, whose basement contacts the water table, for 20 °C and 50% relative humidity indoors. The abscissa is the product of capillary water penetration and absorption coefficient (AB). When this product becomes larger – which is the case for ever more course-porous materials with an ever lower pore volume – dampness first climbs to a maximum height to drop beyond. Very limited heights typify materials with ultrafine or really coarse pores.

Figure 4.17 shows the final damp height after painting such a homogeneous wall, which added 1 m of diffusion thickness to both wall faces. Decreased drying speed now increases that height by a factor of 6! In other words, hiding damp walls behind vapour retarding finishes is no solution. After a few years, wetness will appear again, this time above the vapour retarding finish.

Walls contacting moist soil, brick walls with mortar joints and walls containing dissolved salts show different behaviour. Moist soil still fits with the model on condition that a lower capillary water absorption coefficient and capillary moisture content are assumed. To what extent needs to be tested. Mortar joints in brick walls in turn act as capillary breaks. If the mortar used is coarsely porous, the joints will suck very little

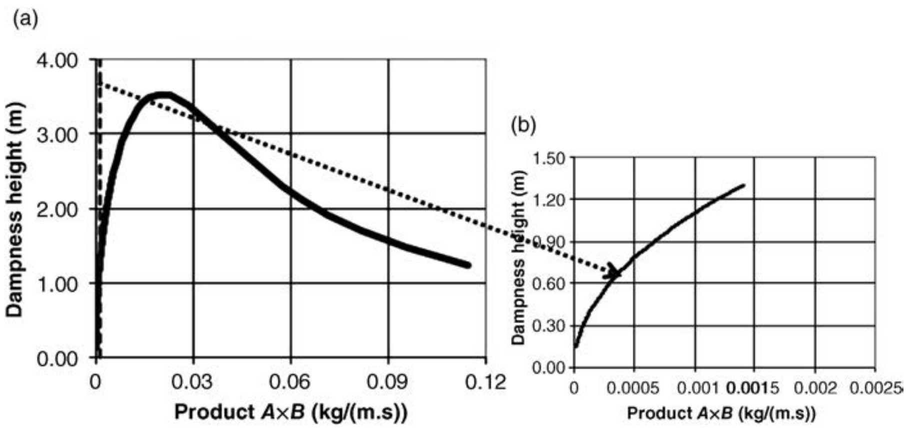

Figure 4.16 Unpainted 30 cm thick partition wall, no joints: damp height at 20 °C, 50% RH and $\beta_i=2.6\times10^{-8}$ s/m. (a) The curve, which details the part between the damp height axis and the dashed vertical in the curve left, represents bricks. (B) the wall.

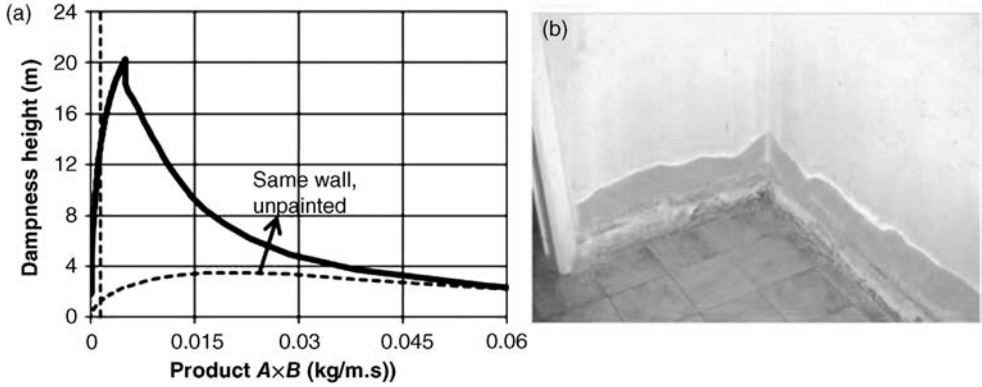

Figure 4.17 (a) The homogeneous wall painted (diffusion thickness 1 m), damp height at 20 °C, 50% RH (b) gypsum plaster short-circuiting the mortar joints.

moisture out of the bricks. In the opposite case, the bricks will pick up very little wetness from the joints. Of course, head and bed joints may turn wet by suction without humidifying the bricks. But even then they retard moisture uptake and limit dampness to a few brick layers, though the plaster often forms a short-circuit as Figure 4.17 shows. Even so, salts mitigate that joint effect, while high concentrations at both wall surfaces and at the moisture front change hygroscopicity to the extent that high moisture content persists even after curing.

4.5.4.4 Avoiding or curing rising damp

In a new construction, insertion just above grade of a section wide watertight membrane in all walls stops rising damp. The same applies above locations where run-off collects, see Figure 4.18.

For retrofit. a first possible cure consists of eliminating suction by inserting watertight membranes or steel plates just above grade in all damp walls. An alternative is filling or

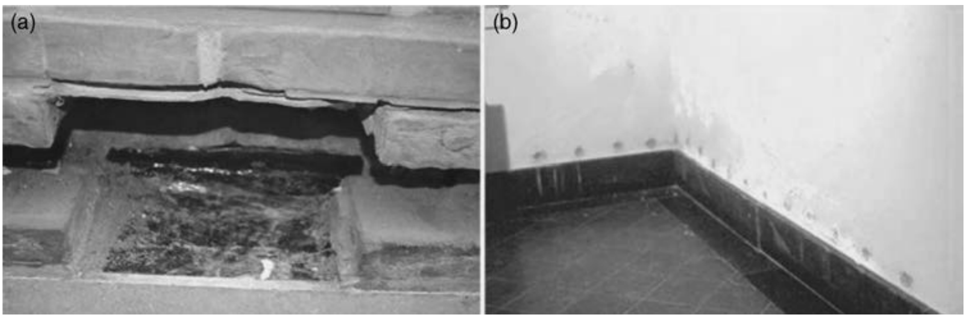

Figure 4.18 (a) Tray avoiding rising damp in the inside leaf of a cavity wall, (b) curing by injection.

making the material pores water repellent by injection or infusion, see Figure 4.18. Unless walls are loaded with salts, in which case hardly anything helps, these are by far the most effective measures. Activating drying is a second possibility. For that, all the retarding finishes have to be removed. This is much less effective than eliminating suction but it sometimes helps.

Repelling dampness could be a third. Electro-kinesis does this, at least in theory. Capillary suction in fact induces a voltage difference between the water in contact and the pore walls. Reversing it should turn suction into repulsion, forcing the water out. This, however, demands energy. In passive electro-kinesis, the electrodes used link a conductor that is embedded above grade in all damp walls to the earth. Corrosion in the contacts between the two delivers the energy needed, though only until breakage. Then, suction restarts. With active electro-kinesis energy is supplied to the conductor by a voltage of less than 2 volts, thus excluding conductor corrosion by avoiding the dissolution of the dampness present in oxygen and hydrogen. But, being active, it consumes electrical energy! And, neither form of electro-kinesis really guarantees drying, merely because dissolved salts make rising damp electrically conducting. So electro-kinesis is a fairly useless measure.

Fourth possibility but also useless is inserting drying pipes above grade in the damp walls. They lack any effect, mainly because the air they contain becomes 100% humid, limiting the drying area to the pipe section. The only conductance left is the surface film coefficient for diffusion at the pipe's aperture, though at high ambient relative humidity, temperature and vapour pressure outdoors give a really weak driving force:

$$G_{\mathrm{v,d,pipe}} = \beta\left[p_{\mathrm{sat}}(\theta_{\mathrm{e}}) - p_E\right]\left(\frac{\pi d_{\mathrm{pipe}}^2}{4}\right)$$

Equally without any benefit is hiding damp walls behind vapour retarding finishes.

A final thing which should not be done when retrofitting is applying any of the effective measures but without first investigating salt presence, especially when it concerns former stable walls, walls that have been in contact with cesspools or walls that have sucked salt-loaded meltwater. No cure for rising damp is of any help then. Hiding behind a non-capillary insulation or a brick veneer is often the only option left.

4.5.5 Pressure heads

4.5.5.1 Definition

The term pressure heads applies to moisture driven by pressure gradients. The differentials that stack, wind and fans generate are generally too small. Instead, the pressure heads constructions below the water table, swimming pool walls (Figure 4.19) and water reservoirs face are often large and constant. The same holds for those that water wells and rain ponds create. To put a figure on it, 10 cm of water gives 1000 Pa, 1 m of water 10 000 Pa.

Figure 4.19 Natatorium, leaking swimming pool wall.

4.5.5.2 Performance requirements

Wetting and leakage should not disturb the function of the spaces whose enclosure faces pressure heads. Thermal insulation, if present, must remain dry, while moistening from outside must stop at the water barrier in the assembly.

4.5.5.3 Modelling

Pressure flow is calculated using Darcy's law for saturated water displacement. The resulting moisture content in open-porous materials mostly exceeds capillary with frost damage for assemblies subjected to temperature swings below 0 °C as one of the risks.

4.5.5.4 Protecting the building fabric

A first possible measure consists of providing drainage around below grade constructions that face rain ponds. Drains collect water using the pressure heads that the pond builds up in the soil, the zero pressure head in the porous pipes and the high water conductivity of the surrounding fill. Between rain events, the ponding water is curving comparable to the temperature field in soils contacting a colder wall (Figure 4.20). The result is a moisture flow per metre run, equal to:

$$G_{\mathrm{w}} = \sqrt{\frac{w_{\mathrm{b}} k_{\mathrm{w,b}}}{\pi t}} \Delta P_{\mathrm{w}}$$

with w_{b} the saturation moisture content in, and $k_{\mathrm{w,b}}$ water conductivity of, the soil, t the time and ΔP_{w} pressure head. Drains function properly as long as the head they face remain below some 0.5 m.

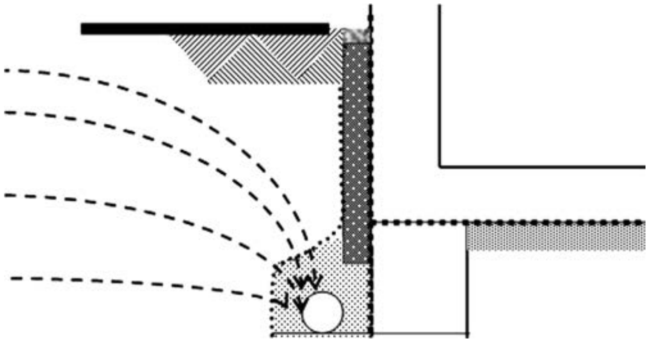

Figure 4.20 Drainage.

A logical second measure is ensuring water tightness of the below grade enclosures. If the related spaces require dryness, the damming construction should form a water barrier at the water head side of the thermal insulation. If usage allows, an alternative is retarded permeation so that the water front in the single-layer damming construction stabilises away from the inside. For that, diffusion from that front to indoors should equal water inflow, giving a steady state relation between the distance (x) from inside and the product of water conductivity (k_a) and vapour resistance factor (μ), assuming the surface film resistance for diffusion is negligible:

$$x = \frac{d}{\frac{\Delta P_w N(k_w \mu)}{p_{sat,x} - p_i} + 1}$$

with ΔP_w water head, $p_{sat,x}$ the saturation pressure at the water front in the wall and p_i the vapour pressure indoors. To function properly, the wall material should combine a low water conductivity with a low vapour resistance factor, which is contradictory as the last requires a high open porosity, large pore diameters and low tortuosity whereas the first needs the inverse.

4.5.6 Accidental leaks

The word accidental embraces uncommon and low probability, but the consequences of such leaks could be disastrous. Figure 4.21 shows a timber-framed dwelling, where a hot water pipe, built into an outer wall, leaked for a couple of years before the amazing amount of damage inflicted led to its detection.

4.5.7 Hygroscopic moisture

4.5.7.1 Definition

The terms ‘hygroscopic’ and ‘sorption’ are used to denote the moisture content in a material in equilibrium with the relative humidity in the pore air (ϕ). Sorption curves are S-shaped, with quite an increase at low relative humidity, a tilted platform between

Figure 4.21 Damage caused by a leaky hot water pipe.

30% and 80% and again a steep rise beyond 80%. Hysteresis compels desorption to stay above the sorption curve – see Figure 4.22 which shows a (de)sorption curve measured between 33% and 98% relative humidity, thus missing the sharp increase below 33%.

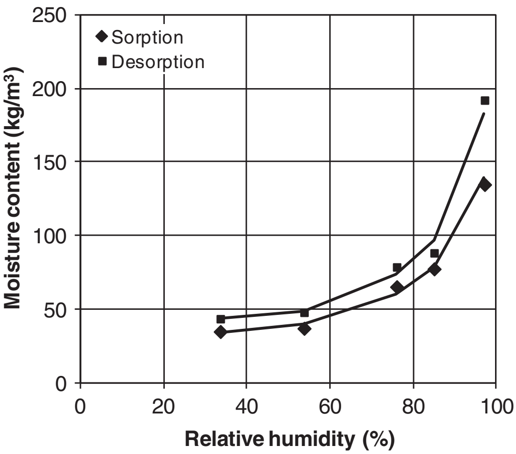

Figure 4.22 Sorption/desorption isotherm.

4.5.7.2 Performance requirements

Hygroscopic moisture reflects an equilibrium state. However, a too high or too low value, which means a too high or too low relative humidity, causes problems. Timber, textiles and paper for example shrink at a relative humidity below 30%. Massive wood panels then crack, paintings are damaged, and so on. A too high relative humidity in turn fosters mould.

4.5.7.3 Modelling

Evaluating cracking risk requires a complex heat–moisture/stress–strain model. Instead, fixing the temperature factor needed to prevent mould in temperate and cold climates is based on a simple rationale. First, knowing the four-week mean vapour pressure indoors (p_i) during the coldest month of the year and assuming 80% as the maximum allowable surface relative humidity, transpose the related vapour saturation pressure into a dew point temperature (θ_d), not to be exceeded indoors during these four weeks:

$$p_{sat,si} = p_i/0.8 \quad p_{sat,si} \rightarrow \theta_d\left(p_{sat,si}\right)$$

Then derive the related mean temperature factor:

$$f_{h_i} \geq \frac{\theta_d\left(p_{sat,si}\right) - \theta_e}{\theta_i - \theta_e}$$

4.5.7.4 Consequences for the building fabric

The model showed that in temperate climates envelope design should guarantee a temperature factor 0.7 or higher everywhere indoors on all opaque parts. Very complex structural thermal bridges require control using appropriate software, included a surface film coefficient inside as mandated by the standard (e.g. 4 W/(m^2.K)) and linked to the operative temperature at the room's centre, 1.7 m above the floor. If 0.7 is respected everywhere, the design complies. Otherwise, adjustment and new controls are needed.

4.5.8 Surface condensation

4.5.8.1 Definition

The term 'surface condensation' commonly covers water vapour condensing on the inside surfaces of any envelope or building fabric part (Figure 4.23). Of course, condensate is also deposited on outside surfaces but this rarely causes trouble.

4.5.8.2 Performance requirements

That on a daily basis drying must win, when outdoors the design temperature for heating reigns, is often the metric advanced, be it that lasting surface condensation on single glass will apparently have no consequences. Anyhow, run-off will moisten the window sashes. So, if made from softwood, they may gradually rot. Reveals that suck condensate deposited on aluminium window frames could turn mouldy. Surface condensation along

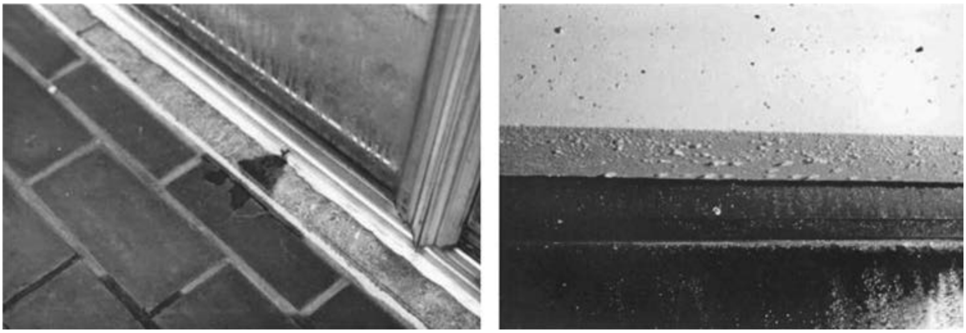

Figure 4.23 Surface condensation.

the perimeter of double or triple glass is a sign of a too high vapour release or failing ventilation indoors. And opaque envelope parts that are a little warmer than these glasses may turn mouldy if the four-week mean relative humidity at their inside surface passes 80% or when occasional surface condensation followed by drying pushes relative humidity temporarily well above 80%.

4.5.8.3 Modelling

Modelling starts with gathering information on the most likely daily mean vapour pressure indoors. If this value exceeds the daily mean inside surface saturation pressure somewhere, condensate will be deposited there:

$$g_c = \beta\left(p - p_{sat,s}\right) \approx 7.4 \times 10^{-9} h_c \left(p - p_{sat,s}\right) \quad (\text{kg}/(\text{m}^2.\text{s})) \tag{4.26}$$

with β the surface film coefficient for diffusion and h_c the convective surface film coefficient. Heat transfer involved is:

$$q = g_c l_b \approx 2.5 \times 10^6 g_c$$

For 1 m^2 of flat assembly, the steady-state thermal balance at the condensing side then becomes:

$$-2.5 \times 10^6 g_c = h_1(\theta_1 - \theta_s) + \frac{\theta_2 - \theta_s}{1/U - 1/h_1}$$

resulting in the following surface temperature:

$$\theta_s = \frac{h_1\theta_1 + U'\theta_2 + 2.5 \times 10^6\, g_c}{U' + h_1} \text{ with } U' = \frac{1}{1/U - 1/h_1} \tag{4.27}$$

In these formulas 1 denotes the condensation and 2 the other side of the assembly with θ_1 and θ_2 the related temperatures, operative indoors and sol-air outdoors. To quantify surface condensation, the system formed by the condensing flux and the temperature equation above is solved iteratively. When after a period of condensation the surface

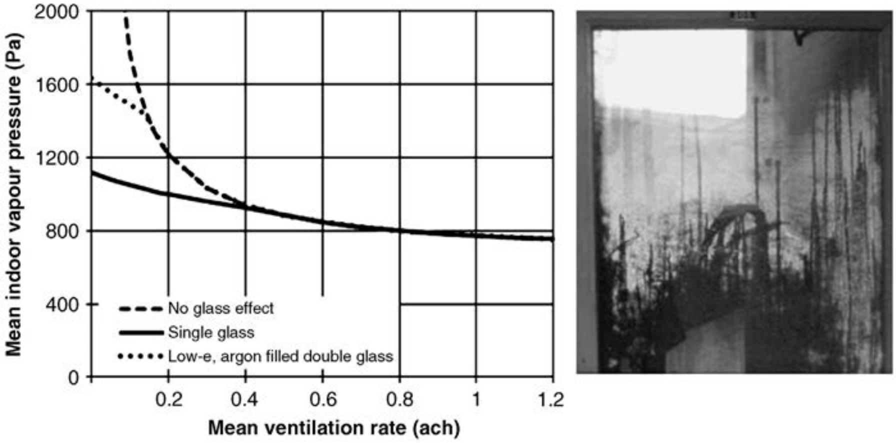

Figure 4.24 Two persons bedroom $4 \times 4 \times 2.5\ \text{m}^3$, $2.52\ \text{m}^2$ of glass. Monthly mean vapour pressure indoors depending on glass type and ventilation rate where the room is occupied 8 hours a day (monthly mean outdoors 2.7 °C, 663 Pa, indoors 13.9 °C).

warms up and sees its saturation pressure passing vapour pressure in the air close by, drying starts and goes on until all condensate has evaporated:

$$\int_{o}^{t} g_{\text{d}} \text{d}t \leq m_{\text{c}} \tag{4.28}$$

Too high vapour pressure or too low inside surface temperature are the culprits indoors, with the first, as explained, pointing to high vapour releases or/and bad ventilation and the second to poor insulation and/or details acting as thermal bridges. Of course, condensation alternating with drying will stabilize vapour pressure indoors at levels that depend on the thermal resistance of the surfaces involved, usually the glazing, and the ventilation rate, see Figure 4.24.

Under-cooling or sudden weather changes, from cold to warm and humid, invoke surface condensation outdoors. The results are icy roads, frost on cars, rime on roofs and on argon-filled low-e double and triple glazing outside. In temperate climates, the winter amounts on well-insulated facades compare with what wind-driven rain deposits.

4.5.8.4 Consequences for the envelope

Insulate well and avoid thermal bridges with too low a temperature factor.

4.5.9 Interstitial condensation

4.5.9.1 Definition

Interstitial condensation refers to vapour deposited as liquid in building assemblies. For a long time, vapour released indoors was assumed to be the only wrongdoer. More

Figure 4.25 Damage caused by interstitial condensation.

recently it has been shown that temperature gradients can force construction moisture, hygroscopic moisture, rising damp and absorbed or drained rain to evaporate and deposit as condensate elsewhere in an assembly. Driving forces are diffusion and, more powerful, air ingress. Design flaws and workmanship errors, albeit often hidden for a long time, are usually the cause of the problems (Figure 4.25).

4.5.9.2 Modelling

In the late 1950s, H. Glaser advanced a simple rationale for checking interstitial condensation in cold storage walls. The method did well because most materials in such enclosure were neither capillary nor hygroscopic, while the assemblies were airtight, the differences in temperature and relative humidity only fluctuated modestly and vapour diffusion was the driver. In the 1960s, some started to use his rationale to judge building assemblies on moisture tolerance, which was a step too far. Building enclosures in fact face transient conditions, airtightness is not guaranteed, the materials used are often capillary and hygroscopic, gravity and pressure heads intervene, and so on. In later years more realistic boundary conditions, capillary redistribution and air egress as a driving force were included, giving birth to the many transient heat, air, moisture models that exist today.

Until the 1990s the Glaser method remained the reference for checking interstitial condensation tolerance of building assemblies, regardless of being far too simple because only airtight parts with non-hygroscopic inside finish, neither a capillary nor a hygroscopic outside cladding and closed cell insulation in between convened. A sad result was a vapour barrier mania that survived for decades. That diffusion only method includes many assumptions.

Geometry	1. Flat assembly composed of plane-parallel layers
Moisture flow	2. Vapour only. False for capillary-porous materials beyond critical moisture content
	3. Diffusion sole driving force. Valid as long as the assemblies and their layers are airtight. Testing and practice show that this is mostly untrue
	4. Hygroscopicity not considered. Eliminates hygric inertia and makes the vapour balance steady state under all circumstances. Softened as an assumption by applying monthly mean boundary conditions
	5. Vapour resistance factors constant. Does not fit with reality but makes calculation easy. An alternative is using different values depending on whether a layer sits at the inside or at the outside of the insulation
Heat flow	6. Equivalent conduction only. Excludes any form of enthalpy flow
	7. Latent heat release far too low to have impact
	8. Thermal inertia not involved. Heat flow is steady state, even under varying boundary conditions. Softened as an assumption by applying monthly mean boundary conditions
	9. Thermal conductivity of all materials constant. Does not fit with reality but makes calculation easy.

Regarding the boundary conditions, slope, orientation and shortwave absorptivity of the outside surface have to be known. The European standard presumes an outside surface protected from sun and under-cooling, so the monthly mean outdoor air temperature applies. A better approach is to use the equivalent temperature for condensation and drying (see Chapter 1). Also needed are the monthly mean vapour pressures outdoors for the location considered and the temperature and vapour pressure indoors. If no measured data is available, following annual mean and amplitude for the temperature indoors can be used:

Building type	Annual mean, °C	Annual amplitude, °C
Dwellings, schools, office buildings	20	3
Hospitals	23	2
Natatoriums	30	2

The monthly mean vapour pressure (p_i) indoors can be calculated if the monthly mean outdoors (p_e), the mean ventilation rate (n in ach), the hourly mean vapour release indoors ($G_{v,p}$), and the built indoor volume (V) are known:

$$p_i = p_e + \frac{R(273.15 + \theta_i)G_{v,p}}{nV}$$

Otherwise, the pivot vapour pressure for the indoor climate class that the building belongs to is used. For the temperature and that climate class related vapour pressure indoors the monthly means follow from:

$$= \textit{annual mean} + \textit{annual amplitude} \times C(t)$$

with $C(t)$ the time function, in Chapter 1 only given for Uccle (Brussels).

Consider first an assembly, which is dry at the start. Fix the thermal and diffusion resistances of all layers. Redraft the assembly in a [diffusion resistance/vapour pressure] axis system and calculate the temperature and saturation pressure in all interfaces (p_{sat}) for the coldest month of the year, typically January (southern hemisphere: July). Coupling the successive interface saturation pressures by straight lines mostly suffices as curve. Draft the vapour pressure line. If intersecting saturation, interstitial condensate is a fact. In this case, trace the tangents from the vapour pressures indoors (face $Z = Z_T$) and outdoors (face $Z = 0$) to the saturation curve. A coinciding point of contact means condensate deposits in that one interface. Otherwise a tangent scan from highest to lowest point of contact fixes all interfaces or zones where deposit happens. The difference in slope per interface or zone between incoming and outgoing tangent then gives the monthly amount condensed:

$$m_c = 86400 d_{\text{mo}} g_c \quad (\text{kg/m}^2) \tag{4.29}$$

with g_c the condensing flux in kg/(m^2.s) and d_{mo} days per month.

With one condensing interface, add the successive amounts that during the colder months condense there and subtract the amounts that during the warmer months dry. Once the deposit left drops below zero, keep that zero during the months that follow until intersection with saturation restarts. Unless annual drying excludes accumulation, condensing will continue until a limit state is reached.

Two or more condensing interfaces complicate the counting. The annual total follows from the algebraic sum of the twelve incoming and outgoing tangent slopes, assuming vapour saturation at their contact points. Assessing the allowance requires the annual total to be redistributed over all condensing interfaces, according to the difference in slope between the arriving and departing tangent in each of them. If condensation zones were found, the derivative of the saturation curve defines the distribution of the deposit in them.

Move now to assemblies where-in one, sometimes more layers contain construction moisture, rain or rising damp. The calculation becomes more complex then. Take one wet layer. Again, redraft the assembly in a [diffusion resistance/vapour pressure] axis system and assume vapour saturation pressure in the wet layers. As evaporation happens in the interfaces with neighbouring layers, connect the wet interface at the inside straight on with the vapour pressure indoors and the wet interface at the outside straight on with the vapour pressure outdoors. If either one intersects saturation, wetness from the moist layer will condense elsewhere in the assembly. The next steps then reflect the dry wall case. Replace the intersecting straight line by the tangents coming from the wet interfaces and from the vapour pressure indoors or outdoors. The points of contact fix the condensation interface or zone, and so on.

More advanced but still not truly realistic is the combined diffusion and convection method, which handles the following assumptions:

Geometry	1. Assembly composed of plane-parallel layers
Moisture flow	2. Vapour only 3. Exfiltration/infiltration and diffusion as driving forces 4. No sorption/desorption 5. Diffusion resistance factor constant
Heat flow	6. The result of equivalent conduction and enthalpy flow 7. Latent heat release too low to be considered 8. No thermal inertia 9. Thermal conductivity constant

The calculation is often restricted to a reference cold week, for Uccle:

Temperature, °C	Relative humidity, %	Radiation, hor. surface, W/m^2	Surface film coefficient, W/(m^2.K)	Wind velocity (free field), m/s
−2.5	95	−30	17	3.8

Slope, orientation, composition, radiant properties of the outside surface, thickness, air permeance, equivalent thermal conductivity and equivalent vapour resistance factor of all layers must be known. First quantify the air flow rate through the assembly. For that, wind, stack and fan induced air pressure differences are needed. Then calculate the thermal and diffusion resistances of all composing layers. Temperature and vapour pressure indoors have to be known. If measured data or best guesses fail, the indoor climate class that the building or room belongs to fixes the values to be used.

If the assembly starts air-dry, calculate the temperature, saturation and vapour pressure in it, the last curving exponentially in the [diffusion resistance/vapour pressure] axis system. Interstitial condensation happens when the vapour pressure curve crosses saturation. If so, calculate the incoming and outgoing tangent exponentials from the vapour pressure indoors and outdoors to the interface where the distance from the vapour pressure exponential to the saturation curve is largest. If none of these two exponentials crosses saturation, condensate deposits in that one interface. Otherwise, a tangent exponentials scan must fix all intermediate condensing interfaces or zones. Quantify the amounts deposited (G_c in kg/(m^2.week)). For assemblies with wet layers, the evaluation runs according to the methodology for diffusion.

4.5.9.3 Performance requirements

Allowance is typically expressed in terms of the annual deposit per m^2 that has no harmful consequences:

Belgium	**Allowance, kg/m^2**
Accumulating deposit	*Limit state*
– Problem-free drainage possible	—
– Frost-resisting, d metre thick stony materials without vapour-tight finish outside	$m_c \le w_{cr} d$
Winter deposit, no accumulation	*Maximum*
– Stony materials that are frost resisting and have a vapour-tight finish at the outside, stony materials that are not frost resisting (both d metre thick)	$\le 0.05 w_{cr} d$
– Wood and moisture proof wood-based materials (plywood, particle board, fibre board, OSB)	$\le 0.03 \rho d$
– Non-moisture proof wood based materials	≤ 0.05
– Foils with slope(s) below 15°	$\le 0.4 - 0.3 s/15$
– Foils with slope(s) beyond 15°	≤ 0.1
– Slightly moisture sensitive insulation materials (mineral fibre, EPS, XPS, PUR)	$\le \max\left[\frac{12.5\lambda}{U_o(0.6-\lambda)}, 0.5\right]$

Switzerland	**Allowance, kg/m^2**
Accumulating deposit	Not allowed
Winter deposit, no accumulation	*Maximum*
– Stony materials	≤ 0.8
– Wood and moisture proof wood-based materials	$\le 0.03 \rho d$
– Non-moisture proof wood based materials	0
– Non-capillary foils with any slope	0.02
– Slightly moisture sensitive insulation materials	$\le 10 d$

In both tables, w_{cr} is critical moisture content in kg/m^3, ρ density in kg/m^3, λ thermal conductivity and U_o the clear wall thermal transmittance of the assembly controlled.

4.5.9.4 Consequences for the building envelope

Most important is a good airtightness of all envelope parts. If this is the case, then a vapour retarder with the right diffusion resistance can still be needed at the warm side of the insulation, unless the diffusion resistance of the composing layers drops from the warmer, more humid to the colder, drier side. As a reminder, the warmer side is indoors in temperate and cold climates and outdoors in hot, humid climates. Of course, conflicts with other moisture sources are not unlikely. Rainproof, vapour-tight outside finishes that are combined with a vapour retarder inside may box up the insulation with layers containing construction moisture. Solar driven vapour flow can force rain buffered in outside finishes to condense against the vapour retarder's insulation side, and so on.

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