



Moisture in Buildings

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1. Moisture in the air

Air contains a quantity of moisture as small particles of water and can, therefore, to a certain limit absorb moisture from the environment. The quantity of moisture (the absolute humidity) the air can absorb depends on the temperature in a way that the higher the temperature, the more moisture can be absorbed in the air. Saturated air contains the maximum absolute humidity at the specific temperature and can, therefore, not absorb any more moisture from the environment.

The relative humidity is defined as the ratio between the absolute humidity in the air and absolute humidity in the air at the same temperature if it was saturated. Therefore, saturated air has a relative humidity of 100%

The absolute humidity has been found empirically as a function of temperature and corresponds to the curve marked with 100% RH in Figure 1 below; see e.g. DS/EN ISO 13788. Figure 1 also shows curves for relative humidity 20%, 40%, 60% and 80%

1.1. Absolute humidity diagram

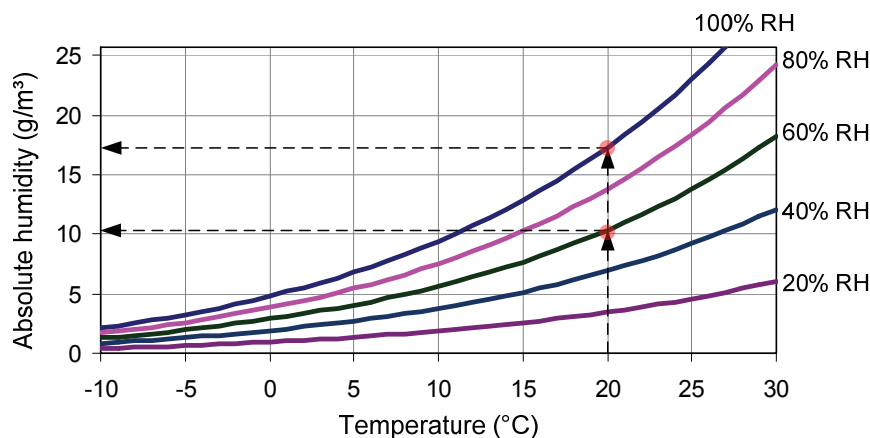


Figure 1. Absolute humidity diagram. Water vapour content as a function of temperature for different relative humidity values (RH). The curve marked with 100% RH corresponds to saturation and is obtained empirically; see e.g. DS/EN ISO 13788. The other curves are obtained by multiplying the relative humidity by the values from the saturation curve.

Figure 1 shows that air at 20 °C has maximum absolute humidity at approximately 17 g/m³ and the absolute humidity in air with a relative humidity of 60%, at the same temperature, will be slightly more than 10 g/m³.

Moreover, the higher the temperatures the more water vapour the air can absorb. This means that the relative humidity falls when cold air is heated with no extra moisture supply. The example in Figure 2 shows that outdoor air with a temperature of 5 °C and a relative humidity of 80% heated to 20 °C will achieve a relative humidity just above 30% in spite that it contains the same amount of water vapour.

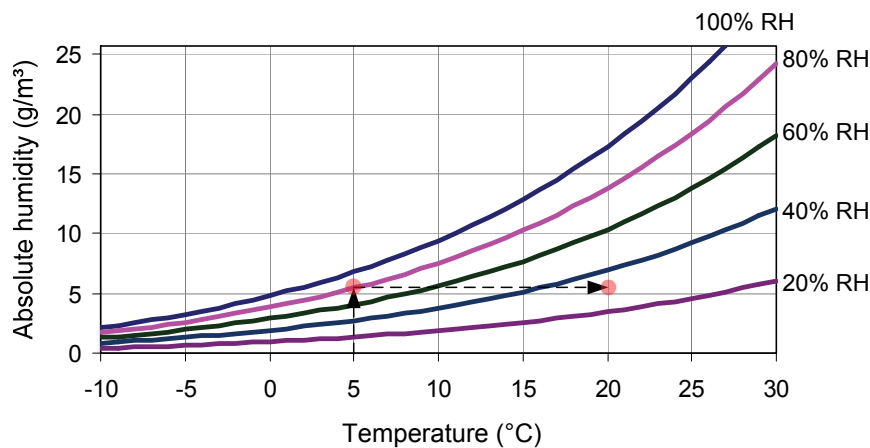


Figure 2. Example used to describe heating with no extra moisture supply, corresponding to a horizontal line to the right in the chart. The example shows heating of 5 °C and 80% RH to a temperature of 20 °C, and it appears that the relative humidity after heating has dropped to just above 30% RH

Alternatively, cooling of air will cause an increase of the relative humidity. The relative humidity in the air increases until saturation is achieved. Additional cooling will release water vapour into the environment. Figure 3 illustrates this with air at 20 °C and a relative humidity of 60%, which is cooled down to 0 °C. At approximately 12 °C the saturation point is reached and this temperature is, therefore, the dew point temperature.

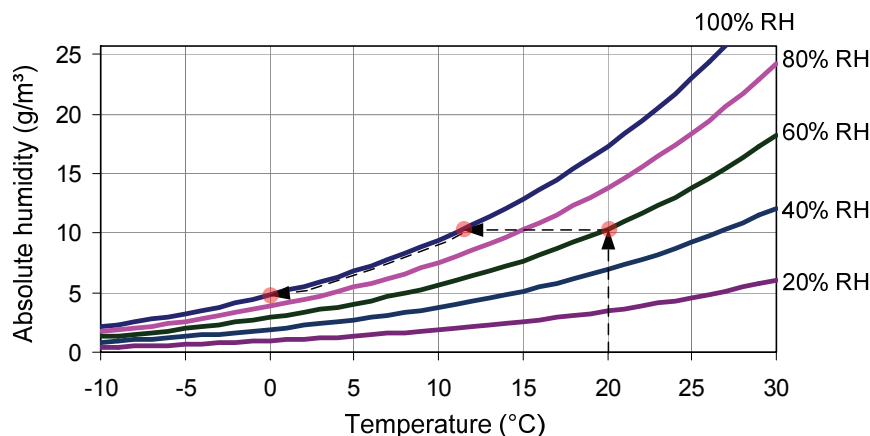


Figure 3. Water vapour diagram. Cooling without additional moisture supply, equivalent to a horizontal line to the left in the figure. The example shows cooling from 20 °C and 60% RH to a temperature of 0 °C. The dew point temperature is approximately 12 °C as the saturation point is reached. It is not possible to cool down further without releasing moisture to the surroundings.

1.2. Water vapour pressure diagram

Alternative to the absolute humidity, the water vapour content can be expressed by the water vapour pressure. The relationship between absolute humidity in kg/m³ (c) and water vapour pressure in Pa (P) can be found by using the formula: $P = c \cdot 461,5 \cdot T$, where T is the temperature in Kelvin.

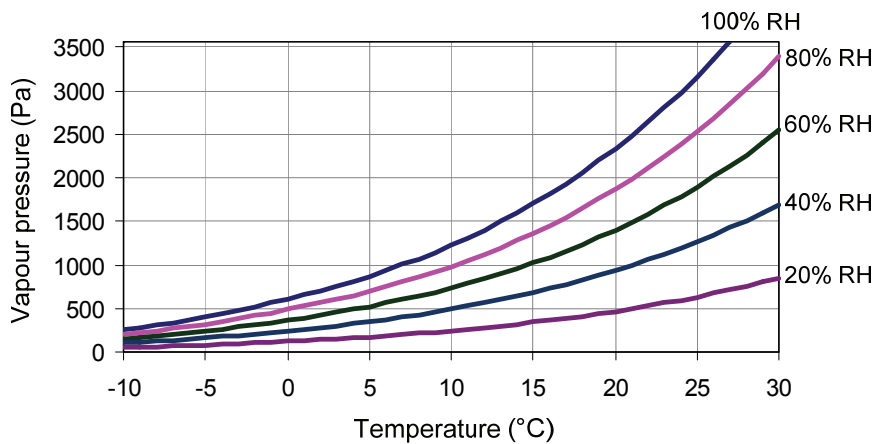


Figure 4. Water vapour pressure diagram. Vapour pressure as a function of temperature

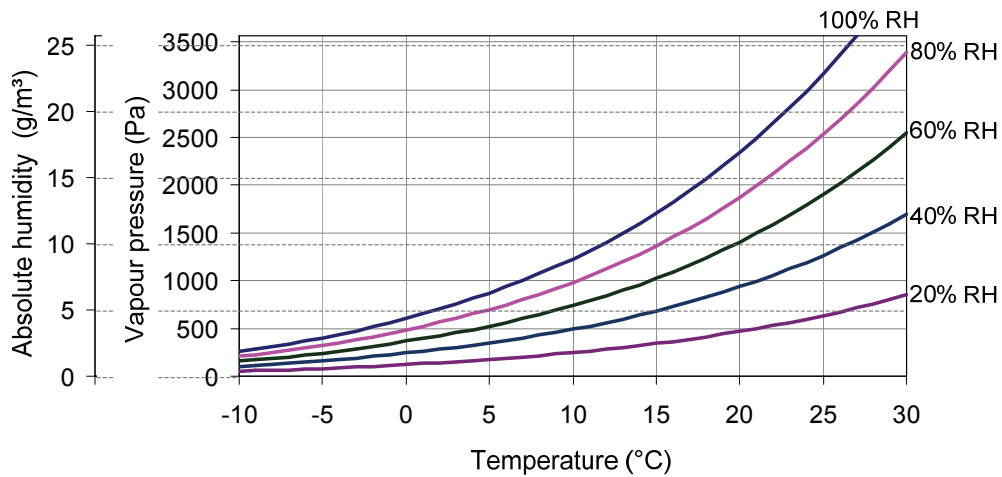


Figure 5. Absolute humidity and water vapour pressure diagram. The saturation curve for absolute humidity and vapour pressure are not completely identical. However, in the temperature range shown, the difference is small, so it is a fair approximation to use the same diagram by simply replacing the y-axis.

Saturation vapour pressure and absolute humidity as a function of temperature, both as table values and as analytical expressions, are given in Appendix D.

1.3. Dew point temperature

Dew point temperature corresponds to the temperature at which the air is saturated. Internal temperatures cooled down strongly, e.g., because of poor insulation or thermal bridges, may reach their dew point temperature at internal surfaces and thereby condensate with many damaging effects to the building component and the building. In an absolute humidity or water vapour pressure diagram, this will be depicted as a horizontal line from internal air state (temperature and relative humidity) to the left until saturation is achieved. At this point, dew point temperature can directly be seen.

Figure 6 gives an example of how to find the dew point temperature in a vapour pressure diagram.

The internal air at 20 °C and relative humidity of 60% (point B in the diagram) is cooled down to saturation (Point C in the diagram), thus enabling the dew point at 12 °C to be read.

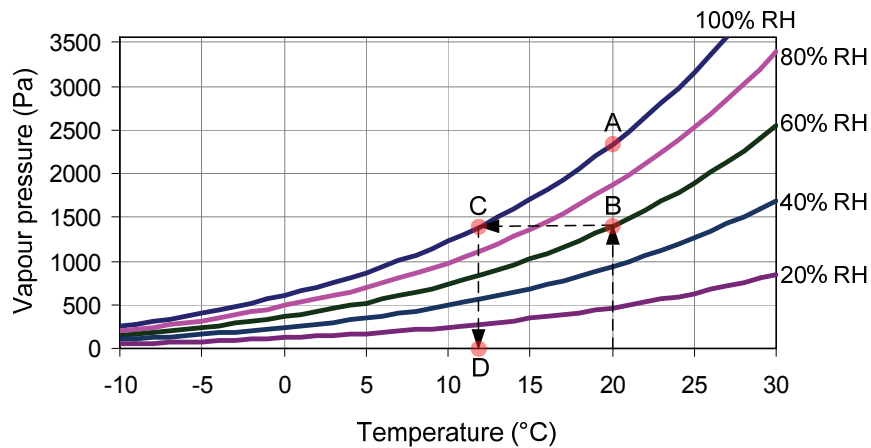


Figure 6. Dew point temperature. Point A: 20 °C and 100% RH. Point B: 20 °C and 60% RH. Point C: 6 °C and 100% RH. The 12°C (Point D) is the dew point temperature of the state in point B.

Dew point can be calculated using the formulas for vapour pressure and temperature in Appendix D, and this calculation will also show a dew point temperature at 12.0 °C

$$t_i = 20 \text{ °C} \quad \text{internal temperature}$$

$$\varphi_i = 60 \% \quad \text{internal relative humidity}$$

Saturation vapour pressure for a temperature of 20 °C (Point A in Figure 6)

$$P_m(20) = 610,5 \cdot e^{17,269 \cdot 20 / (237,3 + 20)} = 2337,0 \text{ Pa}$$

Vapour pressure for a temperature of 20 °C and relative humidity of 60% (Point B)

$$P(t) = \varphi \cdot P_m(t) = 0,60 \cdot P_m(t) = 0,60 \cdot 2337,0 = 1402,2 \text{ Pa}$$

Temperature corresponding to a saturation vapour pressure at 934.78 Pa (Point C / D in Figure 6)

$$t(1402,2) = \frac{237,3 \cdot \ln(1402,2 / 610,5)}{17,269 - \ln(1402,2 / 610,5)} = 12,0 \text{ °C}$$

2. Temperature and relative humidity

The external temperature and relative humidity varies over days and years. Absolute humidity over a day is almost constant whereby the relative humidity changes depending on the temperature. On a summer day, the relative humidity varies from 50% daytime to 100% night-time where dew may be present. On an average summer day, the relative humidity is 75% while winter days on average have relative humidity at approximately 90% despite the fact that the absolute humidity on a winter day (at 5 g/m³) is only approximately half the amount of a summer day.

The internal relative humidity depends on the external condition of temperature and relative humidity and the internal humidity load from perspiration from occupants, machines, laundry, bathing, cooking and the like. Heating of external air will decrease the relative humidity and the internal humidity load will again raise the relative humidity. The absolute humidity (or water vapour pressure) is larger internally than externally and, therefore, make ventilation necessary. Even a vent in the rain will remove moisture from the building.

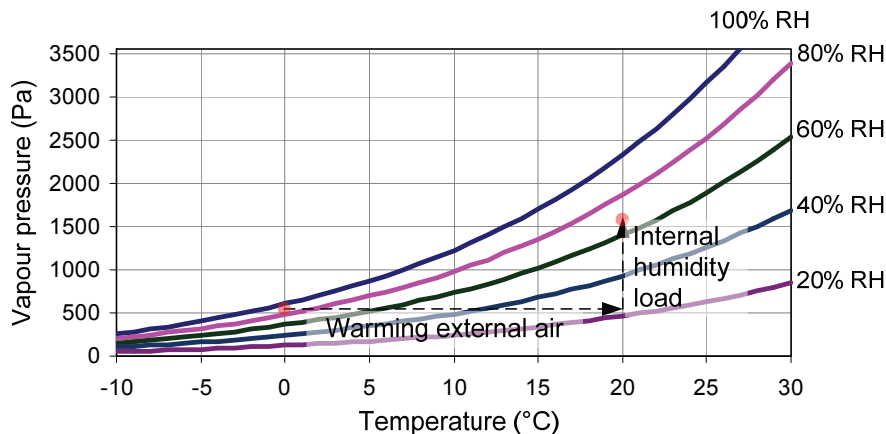


Figure 7. Warming of the external (horizontal line) and internal humidity load (vertical line). The external state is 0°C and 90% RH and the internal state is 20 °C and just above 60% RH

Heating the external air is depicted in Figure 7 as a horizontal line from the external state with temperature and relative humidity and the same vapour pressure (and absolute humidity). The internal humidity load can be illustrated by a vertical line. In this example, the external temperature is 0 °C and relative humidity is 90% RH. Heating the external air to 20 °C, the relative humidity decreases to just above 20% and the internal humidity load causes the relative humidity to rise; in this example to just above 60%

2.1. Humidity classes and Danish moisture classes

Internal humidity load depends on the type of building; e.g., the internal humidity load in a warehouse is less than in a swimming pool. In Denmark, buildings are divided into three moisture classes that denote the buildings' use. These are defined by an absolute internal humidity on a winter day. Moisture class 1 has an absolute internal humidity of less than 5 g/m³, moisture class 2 an absolute internal humidity of 5-10 g/m³ and moisture class 3 an absolute internal humidity above 10 g/m³.

DS/EN ISO 13788 divides the buildings into 5 humidity classes covering the 3 Danish moisture classes with some overlap.

Danish moisture class	Humidity class	Building
1	1	Storage areas
2	2	Offices, shops
	3	Industrial buildings with low humidity load Dwellings with low occupancy
	4	Dwellings with high occupancy Schools and institutions Sports halls
3		Kitchens, canteens
	5	Swimming pools Damp industrial buildings Bathing and dressing rooms

The definitions of the 5 humidity classes are slightly different, defined as a humidity load (or increase in vapour pressure) decreasing by increasing external temperature.

The Danish moisture classes are only defined for the winter period and have, therefore, no conversion to absolute humidity or vapour pressure for the rest of the year. However, it could be advantageous to convert the Danish moisture classes to the same model used in the 5 humidity classes. This could be done by defining the humidity load at 0 °C (5 g/m³ at the transition between moisture classes 2 and 3), convert it to vapour pressure (for 5 g/m³ at 0 °C this is equivalent to 630 Pa) and let this decrease linearly to zero at 20 °C precisely as the definition of the 5 humidity classes. This is illustrated in Figure 8 below.

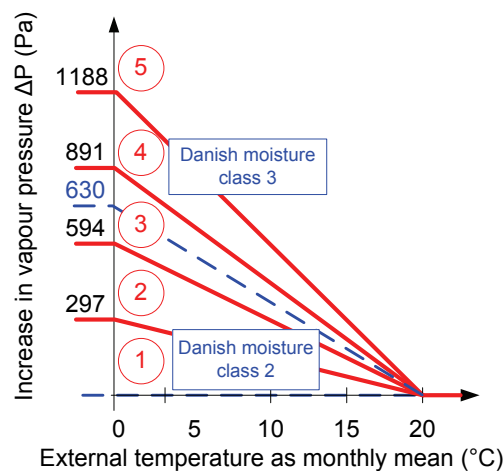


Figure 8. Definition of the 5 humidity classes and conversion of the 3 Danish moisture classes to the same model. Moisture class 1 has no increase in vapour pressure and moisture classes 2 and 3 are enclosed by the dotted line. The 5 humidity classes marked in circles is enclosed by the solid lines

Residential buildings are, according to the table, contained in the Danish moisture class 2 and in humidity classes 3 and 4 and it is remarkable that the vapour pressure and thus the internal relative humidity of residential buildings are estimated very differently in the two class definitions. A moisture analysis using internal relative humidity similar to the Danish moisture class 2 and humidity class 4 can be so markedly different, as the former may show a building component free of

condensation, whilst the latter may show a condensation risk or possibly mould growth risk on internal surfaces.

The internal relative humidity may be determined from the vapour pressure diagram as in Figure 7, where the external air temperature and relative humidity represents the first point in the diagram. Heating is illustrated by a horizontal line to the right in Figure 7 and the final internal state, and thus relative humidity, is obtained by adding the increase in vapour pressure from Figure 8.

Figure 9 outlines the internal relative humidity as a function of the external temperature calculated with monthly averages for temperature and relative humidity for the town Ødum in Denmark; see DMI-weather data in Appendix G. The internal temperature is set to 20 °C.

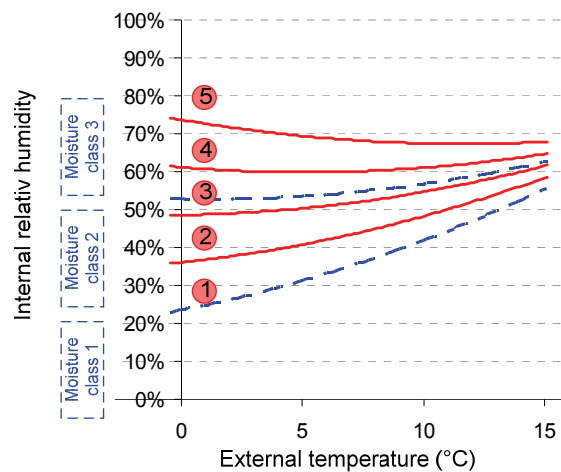
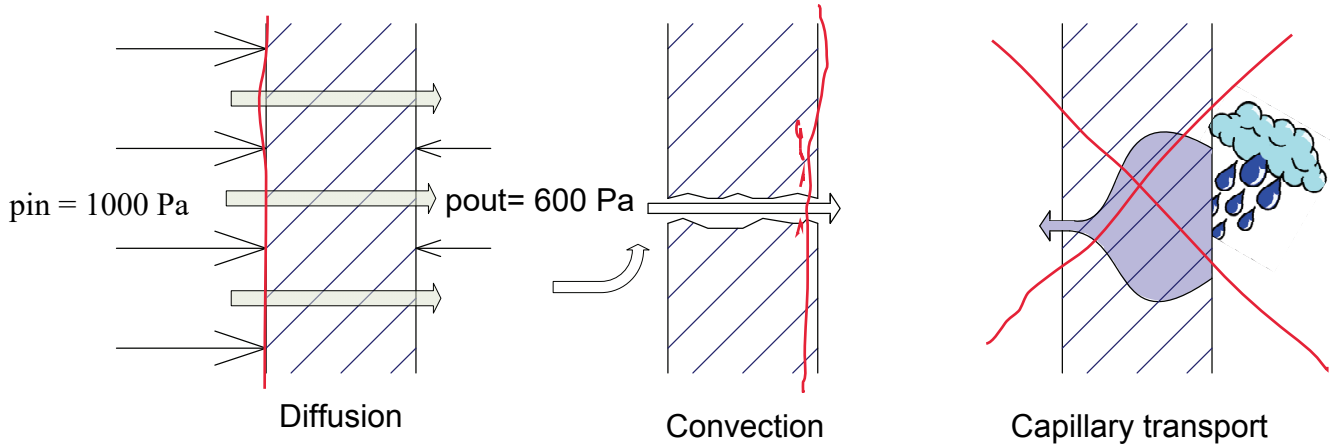


Figure 9. Internal relative humidity as a function of external temperature. Internal temperature of 20 °C and average data for external temperature and RH for the Danish town Ødum, see Appendix G. The Danish moisture classes are bound by the dotted lines and the humidity classes marked in circles are bound by solid lines.

3. Moisture Transport Mechanisms

Moisture transport through a building component can happen by diffusion, convection and capillary transport.



3.1. Diffusion

In moisture transport by diffusion, a pressure difference on either side of a material will drive air and water vapour through the material. There will be diffusion from higher pressure to lower pressure in order to create equilibrium. Diffusion transport is not restricted to air but there will be a diffusion transport through different materials with speeds depending on the material. Internal pressure in a building will usually be higher than external pressure due to the higher internal temperature and there will constantly be an outwards transport of air and water vapour by diffusion.

To reduce the moisture transport by diffusion, diffusion tight membranes in the form of vapour barriers may be inserted in some building components.

3.2. Convection

Moisture transport by convection is air flow through openings and cracks in the structure and will typically be the dominant part of the total moisture transport in older buildings.

To reduce the moisture transport by convection airtight membranes can be used and measures can be taken to minimize leakage through joints and penetrations.

3.3. Capillary transport

Moisture transport from capillary transport is porous materials transporting water. This will only occur with water in liquid form and, therefore, when the dew point is reached and condenses occurs or water from rain, drainage and leaks occur.

The ability to transport water by capillary transport varies for different materials. Some materials

are capillary breaking and do not allow absorption of water, for example through contact with soil, while other materials, such as bricks, will relatively quickly absorb and redistribute water.

4. Temperature flow through a building component

Temperature flow through a building component will be unit linear with a linear progression through each homogeneous layer in the building component. The slope of each of the linear pieces depends on the thermal resistance, R , for each material layer. Figure 10 show a temperature flow through an insulated brick cavity wall:

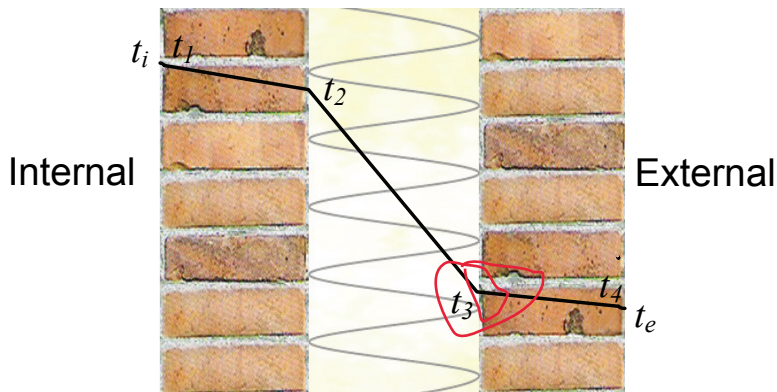


Figure 10. Temperature flow through a brick cavity wall.

The temperature curve can, because of the linear temperature curve in each homogeneous layer, be established by calculating the temperatures at the interfaces between the homogeneous layers, in Figure 10 this is marked by the temperature t_1 , t_2 , t_3 and t_4 .

Internal temperature t_i drops at the surface to t_1 (equivalent to the internal surface temperature) and through the internal brick, the temperature falls linearly to t_2 . In the insulation layer the temperature will decrease (to t_3) again linearly but with a larger descent due to a larger thermal resistance of insulation than for bricks and thus a larger temperature difference between the two interfaces of the insulation layer. The temperature from the interface between the insulation layer and the external brick has decreased through the brick to the temperature t_4 (corresponding to the external surface temperature) and, because of the thermal resistance on the external surface, the temperature drops to the external temperature t_e .

There is no coordinate system applied in Figure 10. However, the x-axis corresponds to the thickness of the building component (the accumulated thickness of the material layers) and y-axis corresponds to the temperature.

Using accumulated thermal resistance as the x-axis, the temperature curve will become a straight line through the structure, see Figure 11. In other words, temperature can simply be determined by drawing a line from the internal temperature to the external temperature. In Figure 11 it is also evident that thermal resistances on internal and external surface affect the temperature curve.

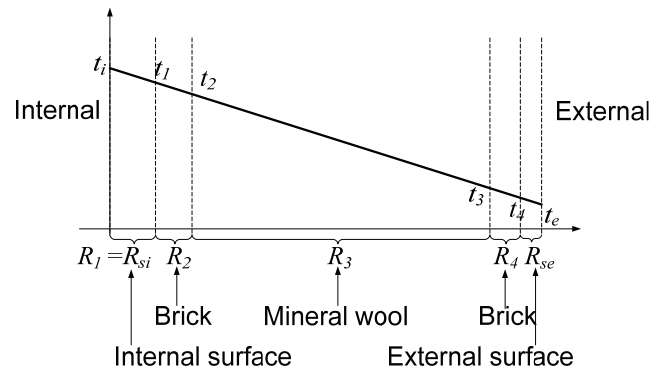


Figure 11. Temperature curve of a brick cavity wall. The x-axis is accumulated thermal resistances.

5. Vapour pressure through a building component

Similarly, for a temperature curve through a building component the vapour pressure is assumed to be linear for each homogeneous layer. The slope will depend on vapour resistances (Z -value) for the different layers. Setting accumulated vapour resistances as the x-axis and vapour pressure as the y-axis would produce a straight line through the building component, see Figure 12.

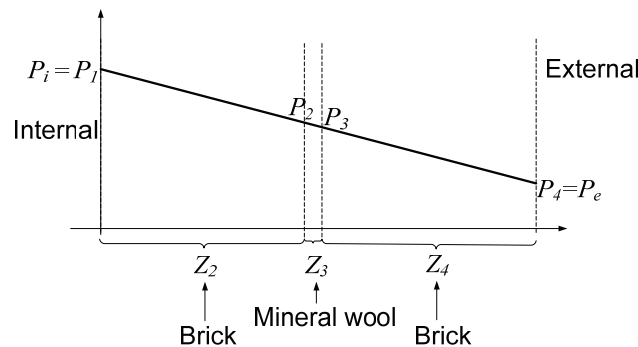


Figure 12. Pressure curve for a brick cavity wall. The x-axis is accumulated vapour resistances

Saturation vapour pressure will not be linear through a homogeneous layer because it depends on the temperature in a non-linearly way. For technical reasons, it could be advantageous to calculate values for saturation vapour pressure only in interfaces between the layers and thus the assumption that through each homogeneous layer, the vapour pressure is linear. The temperature differences between the two interfaces in layers with large thermal resistances, like insulation, will be relatively large providing greater inaccuracies in the linear assumption. Maybe for this reason, DS/EN ISO 13788 recommends that the layers with large thermal resistances be divided into several sub layers.

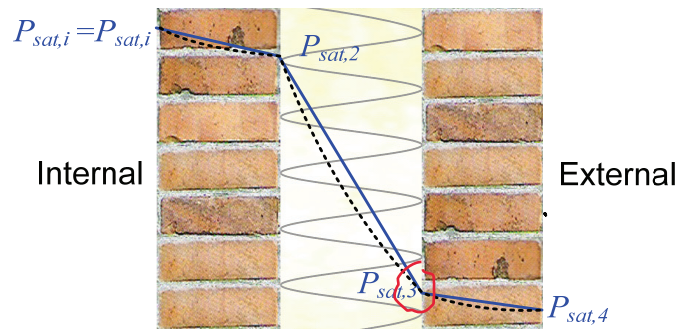


Figure 13. Saturation vapour pressure through a brick cavity wall, similar to the pressure causing condensation. The dotted line represents a curve through each layer with the calculated values in the transitions between each layer. The solid line represents a linear approximation of saturation vapour pressure through each layer.

In Figure 13, the saturation vapour pressure through the building component is marked by the dotted curve, while the converged saturation vapour is the unit linear function marked with the solid line. Dividing the insulation layer into several sub layers will ensure a better approximation.

6. Graphical determination of condensation

Using accumulated vapour resistances as the x-axis and vapour pressure as the y-axis would give us a straight line if no condensation occurred, see, e.g., Figure 12.

Method:

1. Set the vapour pressure as the y-axis and accumulated vapour resistances as the x-axis. Draw a straight line from the internal vapour pressure to the external vapour pressure.
2. Calculate the saturation vapour pressure in the interfaces between the layers using formulas or table values from Appendix D or diagrams in Appendix C. Draw straight lines between the points.
3. If some of the line parts of the saturation vapour pressure intersect the line from the vapour pressure, condensation is achieved. The vapour pressure must then be corrected so that it consists of two or more line segments describing the shortest possible path from the internal vapour pressure P_i to the external vapour pressure P_e without intersecting the saturation vapour pressure curve. In the example in Figure 14, the vapour pressure curve will be corrected to go from P_i to $P_{sat,3}$, and again with a new slope from $P_{sat,3}$ to P_e .

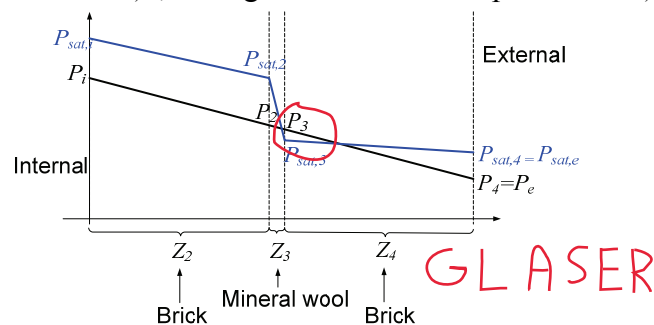


Figure 14. Vapour pressure and saturation vapour pressure through a building component. The x-axis is accumulated vapour resistances (Z-values). The intersection point indicates that condensation occurs.

The example in Figure 14 shows that there will be a dew point in the interface between the mineral wool layer and the external brick layer as the vapour pressure and saturation vapour pressure lines intersect immediately before this interface. Because the vapour pressure cannot exceed saturation vapour pressure, the vapour pressure curve consists of two straight line segments instead of one, the first line segment from P_i to the dew point marked as $P_{sat,3}$ in Figure 14 and the second line segment from $P_{sat,3}$ to P_e .

7. Graphical determination of necessary vapour resistance

The internal and external vapour pressures are determined only by means of the internal and external temperature and relative humidity and are not affected by any change in the design. To ensure a building component without condensation risk, the vapour pressure has to be presented as a straight line that does not intersect the saturated vapour pressure.

Graphically, one could imagine that the internal vapour pressure point (P_i) is moved horizontally to the left until a straight line from this point to the external vapour pressure can be drawn without intersecting the saturated vapour pressure.

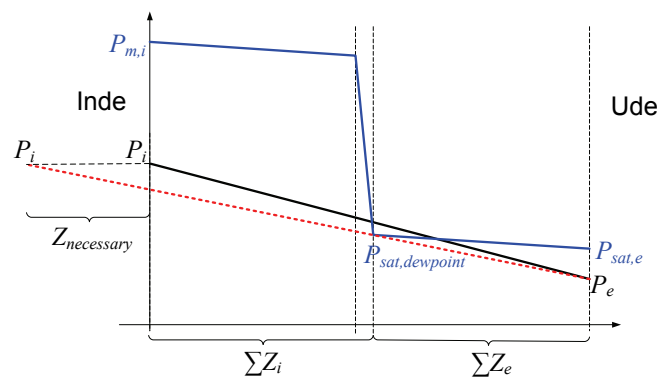


Figure 15. Necessary Z-value. The point P_i is moved horizontally so far to the left that a straight line between that point and the external point P_e does not intersect the saturated vapour pressure line. Here, tangential to the point marked as $P_{sat, dew point}$.

Using geometric considerations, the formula for determining $Z_{necessary}$ will be found as:

$$Z_{necessary} = \frac{\Delta P_i}{\Delta P_e} \cdot \sum Z_e - \sum Z_i \quad \text{where } \Delta P_i = P_i - P_{sat, dewpoint} \quad \text{og } \Delta P_e = P_{sat, dewpoint} - P_e$$

It should be noted that the necessary vapour resistance, $Z_{necessary}$, corresponds to the vapour pressure just reaching dew point, which of course is unacceptable. As an example, material layers of wood may achieve critical moisture when the relative humidity exceeds 75% RH. However, replacing $P_{sat, dewpoint}$ with $0.75 \cdot P_{sat, dewpoint}$ when possible will only ensure that this very interface has a relative humidity of 75%.

Alternatively, the value of $Z_{necessary}$ should be used as a guideline to make a choice of vapour barrier with a specific vapour resistance and then make another measurement of the possible dew points.

8. Surface Condensation – simplified method after DS/EN ISO 13788

To avoid the risk of mould growth on internal surfaces, the relative humidity at the internal surface, φ_{si} according to DS/EN ISO 13788, should not exceed 80% for several days in succession. Alternatively, in the Danish version of SBI-216, the guide for the Danish Building Regulations 2008 it is stated that the critical relative humidity on the surface of a material should be less than 75% in the case that the critical moisture content of the material is not known in advance.

A simple method would be to calculate the internal surface temperature t_{si} , and internal surface vapour pressure, P_{si} . The relative humidity on the surface φ_{si} can then be calculated as the vapour pressure P_{si} divided by the saturation vapour pressure, $P_{sat}(t_{si})$

8.1. Example: brick cavity wall

t_e	= -0,4 °C	External temperature (average for January in Ødum 1961-1990)
φ_e	= 91%	External relative humidity (average for January in Ødum 1961-1990)
t_i	= 20 °C	Internal temperature
φ_i	= 61,1%	Internal relative humidity (from moisture class 3)
R_{si}	= 0,25 $\frac{W}{m^2K}$	Internal surface thermal resistance (set according to DS/EN ISO 13788)
$\sum R$	= 3,97 $\frac{W}{m^2K}$	Accumulated thermal resistances

Internal surface temperature:

$$t_{si} = t_i - \frac{R_{si}}{\sum R} \cdot (t_i - t_e)$$

$$t_{si} = 20 - \frac{0,25}{3,97} \cdot (20 - (-0,4)) = 18,7 \text{ °C}$$

Saturation vapour pressure at internal surface:

$$P_{sat}(t) = 610,5 \cdot e^{17,269 \cdot t / (237,3+t)} \quad (\text{Can be used when } t \geq 0, \text{ see Appendix D})$$

$$P_{sat}(18,7) = 610,5 \cdot e^{17,269 \cdot 18,7 / (237,3+18,7)} = 2155,4 \text{ Pa}$$

Vapour pressure at internal surface:

$$P_{si} = P_i = \varphi_i \cdot P_{sat}(t_i)$$

$$P_{si} = 0,611 \cdot (610,5 \cdot e^{17,269 \cdot 20 / (237,3+20)}) = 1427,9 \text{ Pa}$$

Relative humidity at the internal surface:

$$\varphi_{si} = \frac{P_{si}}{P_{sat}(t_i)}$$

$$\varphi_{si} = \frac{1427,9}{2155,4} = 0,66 = 66\% < 80\% \Leftrightarrow OK$$

In principle, calculations have to be performed for each month with average values for external temperature and relative humidity in order to verify that the relative humidity at the internal surface φ_{si} does not exceed 80% (or 75%) in any of the 12 months.

The table below shows the calculation of the relative humidity on the internal surface of the brick cavity wall. The internal temperature is assumed to be 20 °C and the internal relative humidity is set according to humidity class 3, i.e., dwellings with low occupancy. External temperatures and relative humidity are taken from a DMI-weather report for Ødum, see Appendix G. The relative humidity at the internal surface is within a range of 60% - 66.5% and not at any time near the critical value of 80%.

Month	External Temperature T_e (°C)	External RH φ_e (%)	Internal Temperature t_i (°C)	Internal RH, φ_i (%)	Internal surface temperature t_{si} (°C)	Internal surface vapour pressure P_{si} (Pa)	Internal surface saturated vapour pressure, $P_{sat,si}$ (Pa)	Internal surface RH, φ_{si} (%)
January	-0,4	91,0%	20,0	61,1%	18,7	1429	2157	66,2%
February	-0,5	90,0%	20,0	60,7%	18,7	1418	2157	65,8%
March	1,8	86,0%	20,0	60,3%	18,9	1409	2176	64,7%
April	5,5	77,0%	20,0	57,4%	19,1	1341	2208	60,7%
May	10,7	73,0%	20,0	57,9%	19,4	1353	2254	60,0%
June	14,0	75,0%	20,0	62,7%	19,6	1466	2283	64,2%
July	15,1	76,0%	20,0	65,1%	19,7	1522	2293	66,4%
August	15,1	76,0%	20,0	65,1%	19,7	1522	2293	66,4%
September	12,0	82,0%	20,0	64,4%	19,5	1506	2265	66,5%
October	8,5	86,0%	20,0	62,7%	19,3	1466	2234	65,6%
November	4,2	89,0%	20,0	61,5%	19,0	1438	2197	65,4%
December	1,2	91,0%	20,0	61,8%	18,8	1444	2171	66,5%
Annual average	7,3	82,7%	20,0	60,3%	19,2	1410	2223	63,4%
Average for October to April	2,9	87,1%	20,0	60,6%	18,9	1417	2186	64,8%

9. Condensation in building components – simplified method after DS/EN ISO 13788

Glaser's condensation method (a steady-state method) is a simplified method to identify any condensation areas in building components and critical internal surface temperatures or relative humidity. The method only takes diffusion into account and it is anticipated that the building component prior to the calculation does not include any accumulated water vapour.

The approach is to:

1. Divide the building component into a number of homogeneous layers, i.e., with the same thermal resistance and vapour resistance throughout the entire layer. Typically, each layer

corresponds to a material layer – however, it is recommended that layers with large thermal resistances, like insulation, be divided into several sub layers.

2. Determine the temperature in each interface between layers.
3. Determine saturation vapour pressure for the specific temperatures in the interfaces.
4. Determine vapour pressure in each interface from the temperature in the interface and the vapour resistance of the layer. If the vapour pressure at any point exceeds the saturation vapour pressure there will be condensation, and the vapour pressure is set equal to the saturation vapour pressure.

9.1. Example: brick cavity wall

t_e	= -0,4 °C	External temperature (average for January in Ødum 1961-1990)
φ_e	= 91%	External relative humidity (average for January in Ødum 1961-1990)
t_i	= 20 °C	Internal temperature
φ_i	= 61,1%	Internal relative humidity (from moisture class 3)

The building component consists of two 108 mm brick walls with 125 mm insulation in the cavity. Data for thermal conductivity and vapour resistance is shown in the table below. Text and data in italics (and yellow background) is input for the calculation.

	Material layer thickness, t (m)	Thermal conductivity, λ (W/(m·K))	Thermal resistance, R (m ² ·K/W)	Temperature, t (°C)	Saturation vapour pressure, Pm (Pa)	Permeability, d (kg/(m·s·GPa))	Vapour resistance, Z (GPa·m ² :s/kg)	Vapour pressure without correction (Pa)	Vapour pressure (adjusted), P (Pa)	φ (%)
				20,0	2337			1428	1428	61,1%
Internal air			0,25	18,7	2157			1428	1428	66%
<i>Brick (internal)</i>	0,108	0,670	0,16	17,9	2050	0,019	5,684	997	716	35%
<i>Mineral wool</i>	0,125	0,037	3,38	0,5	634	0,190	0,658	947	634	100%
<i>Brick (external)</i>	0,108	0,780	0,14	-0,2	601	0,020	5,400	538	538	89%
External air			0,04	-0,4	591			538	538	91%
			ΣR 3,97				ΣZ 11,742		ΔP 890	
							ΣZ_i 6,342		ΔP_i 794	
							ΣZ_e 5,400		ΔP_e 96	

Condense

Thermal resistance, R_k :

Internal surface thermal resistance, R_{si} set according to DS/EN ISO 13788 to 0,25 W/(m·K) determining condensation risk. External surface thermal resistance, R_{se} generally set to 0,04 W/(m·K). The others are determined by:

$$R_k = \frac{S_k}{\lambda_k}$$

$$R_{\text{Mineral wool}} = \frac{0,125}{0,037} = 3,38 \frac{m^2 K}{W}$$

Temperature in the interface between two layers:

$$t_k = t_{k-1} - \frac{R_k}{\sum R} \cdot (t_i - t_e)$$

$$t_{\text{Mineral wool}} = t_{\text{Brick (internal)}} - \frac{3,38}{3,97} \cdot (20 - (-0,4)) = 17,9 - \frac{3,38}{3,97} \cdot (20 - (-0,4)) = 0,5 \text{ } ^\circ\text{C}$$

With temperature in the interface between the insulation and the external brick layer, i.e. after layer representing the index k .

Saturation vapour pressure:

$$P_{sat}(t) = 610,5 \cdot e^{21,875 \cdot t / (265,5+t)} \quad (\text{Can be used when } t < 0, \text{ see Appendix D})$$

$$P_{sat}(t) = 610,5 \cdot e^{17,269 \cdot t / (237,3+t)} \quad (\text{Can be used when } t \geq 0, \text{ see Appendix D})$$

Vapour resistance:

The vapour resistance for layer k , Z_k is typically found as table values for materials such as membranes. This can also be calculated using the permeability for material layer k , or by the μ -value, which indicates the ratio between permeability for air and permeability the material layer

$$\mu_k = \frac{d_{air}}{d_k} \quad \text{and the air permeability is: } d_{air} = 1,9 \cdot 10^{-10} \frac{kg}{m \cdot s \cdot Pa} = 0,19 \frac{kg}{m \cdot s \cdot GPa}$$

A μ -value of 1 corresponds to a material layer with permeability similar to a layer of air. A μ -value of 10 corresponds to material layer that can be described as an equivalent air layer with a thickness 10 times greater than the actual thickness and hence a permeability 1/10 of a layer with a μ -value of 1. The higher the μ -value the lower the permeability and thus the greater vapour resistance (Z -value).

The relationship between μ -value and vapour resistance is given by:

$$Z_k = \frac{\mu_k \cdot S_k}{d_{air}}$$

In this example vapour resistance is calculated by the formula:

$$Z_k = \frac{S_k}{d_k}$$

$$Z_{\text{Mineral wool}} = \frac{S_{\text{Mineral wool}}}{d_{\text{Mineral wool}}} = \frac{0,125}{0,19} = 0,658 \frac{m \cdot s \cdot GPa}{kg}$$

It should be noted that the unit for $d_{\text{Mineral wool}}$ is $\frac{\text{kg}}{\text{m} \cdot \text{s} \cdot \text{GPa}}$ in place for SI unit $\frac{\text{kg}}{\text{m} \cdot \text{s} \cdot \text{Pa}}$. In calculating the vapour pressure only relative values of Z are used, therefore the unit is irrelevant. In this example $d_{\text{Mineral wool}}$ has the same value as d_{air} , i.e. $\mu_{\text{Mineral wool}} = 1$.

Vapour pressure in the interface between layers (before any correction):

$$P_k = P_{k-1} - \frac{Z_k}{\sum Z} \cdot \Delta P \quad \text{where } \Delta P = (P_i - P_e)$$

$$P_{\text{Mineral wool}} = P_{\text{Brick (internal)}} - \frac{0,183}{3,341} \cdot (1428 - 538) = 1007 - \frac{0,183}{3,341} \cdot (1428 - 538) = 958 \text{ Pa}$$

Since this value exceeds saturation vapour pressure in this interface (which is at $P_{\text{sat}} = 634 \text{ Pa}$), condense will occur in the interface between insulation and the external brick.

Calculation of vapour pressure throughout the building component must now be repeated because saturation cannot be exceeded. One can imagine the building component consisting of two parts separated by the interface with the condensation point. New values for $\sum Z$ and ΔP , from the internal and external sides, respectively, are calculated.

Vapour pressure in the interface between layers (corrected):

Vapour pressure from the internal side to the dew point is calculated as:

$$P_{k,\text{dewpoint}} = P_{k-1} - \frac{Z_k}{\sum Z_i} \cdot \Delta P \quad \text{where } \Delta P = (P_i - P_{\text{dewpoint}})$$

$$P_{\text{Brick (internal)}} = P_{\text{si}} - \frac{1,579}{1,762} \cdot (1428 - 634) = 1428 - \frac{1,579}{1,762} \cdot (1428 - 634) = 716 \text{ Pa}$$

Vapour pressure from the dew point to the external side is calculated as:

$$P_{k,\text{dewpoint}} = P_{k-1} - \frac{Z_k}{\sum Z_e} \cdot \Delta P \quad \text{where } \Delta P = (P_{\text{dewpoint}} - P_e)$$

$$P_{\text{Brick(external)}} = P_{\text{Mineral wool}} - \frac{1,579}{1,579} \cdot (634 - 538) = 634 - \frac{1,579}{1,579} \cdot (634 - 538) = 634 \text{ Pa}$$

Since there is no more than one layer after the dew point (mineral wool), the calculation is trivial, as: $P_{\text{Brick (external)}} = P_e$

Relative humidity:

It is not necessary to calculate the relative humidity but it may be easier to see when saturation vapour pressure is reached, namely interfaces with relative humidity of 100%:

$$\varphi_k = \frac{P_k}{P_{\text{sat}}(t_k)}$$

$$\varphi_{\text{Brick (internal)}} = \frac{P_{\text{Brick (internal)}}}{P_{\text{sat}}(t_{\text{Brick (internal)}})} = \frac{716}{2050} = 0,35 = 35\%$$

An advantage of calculating the relative humidity is that the relative humidity at the internal surface can easily be found. It is used in the study of mould growth risk on the internal surface, as in the

example in the previous section. The value of this is 66% and, as this is less than 80% (and 75%), there is no risk for mould growth on the internal surface.

Graphical overview of the example:

The example of a brick cavity wall shown in the table:

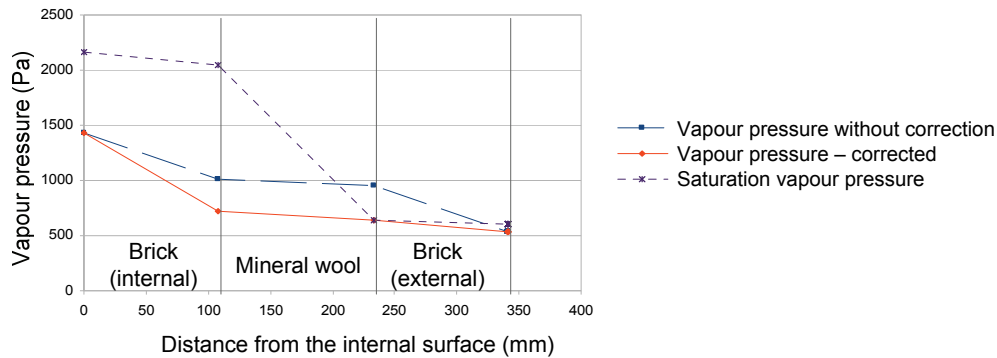


Figure 16. Vapour pressure before and after correction and saturation vapour pressure for a brick cavity wall.

The intersection point of the curve for saturation vapour pressure and vapour pressure before correction indicates that condensation occurs. The corrected vapour pressure curve and saturation vapour pressure are identical in the interface after the intersection point.

Alternatively, using accumulated vapour resistances as x-axis, the vapour pressure curve before correction will be a straight line through the building component. The corrected vapour pressure curve is a straight line before the dew point and again after the dew point.

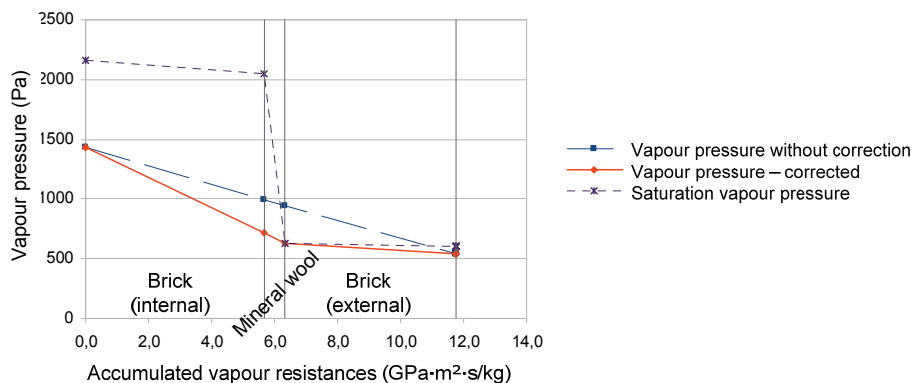


Figure 17. Vapour pressure before and after correction and saturation vapour pressure for a brick cavity wall. The x-axis is accumulated vapour resistances.

In this example, one layer per material layer is applied and thus being a calculation with 3 layers. DS/EN ISO 13788 recommends that layers with thermal resistances above 0.25 m²K/W are divided into several sub layers. In this case the insulation layer should be divided into 14 sub layers. However, this would not change the result because the dew point would still be exactly at the same

point, namely the interface between the insulation layer and the external brick, and the corrected vapour pressure curve, and thus the amount of accumulated moisture would be unchanged.

10. Water accumulation in the building component

If condensation should occur, a given amount of water will be accumulated in the building component. This can be calculated as the difference between the amount of moisture carried into the building component and the amount of moisture being carried out.

The amount of moisture transported can be calculated using the following formula:

$$c_{accumulated} = c_{inwards} - c_{outwards} \quad \text{where} \quad c_{inwards} = \frac{\Delta P_i}{\sum Z_i} \quad \text{and} \quad c_{outwards} = \frac{\Delta P_u}{\sum Z_u}$$

In the example from section 9.1 of a brick cavity wall it would be:

$$c_{inwards} = \frac{\Delta P_i}{\sum Z_i} = \frac{794 \text{ Pa}}{6,342 \cdot 10^9 \text{ Pa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}} = 1,2520 \cdot 10^{-7} \text{ kg}/(\text{m}^2 \text{s})$$

$$c_{outwards} = \frac{\Delta P_e}{\sum Z_e} = \frac{96 \text{ Pa}}{5,400 \cdot 10^9 \text{ Pa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}} = 1,7778 \cdot 10^{-8} \text{ kg}/(\text{m}^2 \text{s})$$

$$c_{accumulated} = 1,2520 \cdot 10^{-7} - 1,7778 \cdot 10^{-8} = 1,0742 \cdot 10^{-7} \text{ kg}/(\text{m}^2 \text{s})$$

In grams per m², the amount of accumulated water in the entire month (30 days) will be

$$c_{accumulated} = 1,0742 \cdot 10^{-7} \cdot 3600 \cdot 24 \cdot 30 \cdot 1000 = 278,4 \text{ g}/\text{m}^2 \text{ per month}$$

10.1. Estimates of moisture accumulation and drying out

An estimate calculation of moisture accumulation and drying out is described in a Danish compendium by Olfert Andersen. In this compendium, moisture accumulation is as described above and the heating period is set to 225 days. Data for temperature and relative humidity should be an average of the coldest of the 225 days in the year, or simply by calculating an average for the months from October to April. For Ødum in Denmark, this corresponds to an external temperature of 2.9 °C and a relative humidity of 87%, see Appendix G.

The example with a brick cavity wall with $t_i = 20 \text{ °C}$, but the values $t_u = 2.9 \text{ °C}$, $\varphi_u = 87\%$ and $\varphi_i = 60.6\%$ (moisture class 3) will give the following estimates of accumulation in the heating period:

$$c_{inwards} = \frac{\Delta P_i}{\sum Z_i} = \frac{622 \text{ Pa}}{6,342 \cdot 10^9 \text{ Pa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}} \cdot 3600 \cdot 24 \cdot 225 = 1,9066 \text{ kg}/\text{m}^2 \text{ for 225 days}$$

$$c_{outwards} = \frac{\Delta P_e}{\sum Z_e} = \frac{140 \text{ Pa}}{5,400 \cdot 10^9 \text{ Pa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}} \cdot 3600 \cdot 24 \cdot 225 = 0,5040 \text{ kg}/\text{m}^2 \text{ for 225 days}$$

$$c_{accumulated} = c_{inwards} - c_{outwards} = 1,9066 - 0,5040 = 1,4026 \text{ kg}/\text{m}^2 \text{ for 225 days}$$

The drying out period is set to 140 days, where internal and external states each are 12 °C and 60% RH and the state at the of condensed layer is 12 °C and 80% RH as long as there is drying out.

Vapour pressure for $t = 12$ °C and $\phi = 60\%$ RH is 1123 Pa and $t = 12$ °C and $\phi = 80\%$ RH is 842 Pa, see Appendix C or D. This gives the following estimate for the amount of drying out:

$$c_{inwards} = \frac{(P_{dewpoint} - P_i)}{\sum Z_i} = \frac{(1123 - 842) \text{ Pa}}{6,342 \cdot 10^9 \text{ Pa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}} \cdot 3600 \cdot 24 \cdot 140 = 0,5359 \text{ kg}/\text{m}^2 \text{ for 140 days}$$

$$c_{outwards} = \frac{(P_{dewpoint} - P_e)}{\sum Z_e} = \frac{(1123 - 842) \text{ Pa}}{5,400 \cdot 10^9 \text{ Pa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}} \cdot 3600 \cdot 24 \cdot 225 = 0,6294 \text{ kg}/\text{m}^2 \text{ for 140 days}$$

$$c_{drying\ out} = c_{inwards} + c_{outwards} = 0,5359 + 0,6294 = 1,1653 \text{ kg}/\text{m}^2 \text{ for 140 days}$$

Since moisture accumulation is greater than the amount of drying out, there will according to this estimate model be an overall accumulation of moisture from year to year in the building component. The annual amount of accumulated moisture will be:

$$c_{accumulated, year} = c_{accumulated} - c_{drying\ out} = 1,4026 - 1,1653 = 0,2373 \text{ kg}/\text{m}^2 \text{ per year}$$

10.2. Moisture accumulation and drying out after DS/EN ISO 13788

The method of calculation of the moisture accumulation and drying out in a building component is:

1. Use Glaser as described in section 9 to identify any condensation risk. As the inputs monthly averages for temperature and relative humidity from a starting month is used. Use, e.g., standard weather data or factual values. A strategy to find the starting month is to make a calculation with an initial starting month (in Denmark October will usually be best choice for a starting month):
 - a. If no condensation occurs in this calculation, make the same calculation for the following month and the month after that, and so on. Repeat this process until you find a month with condensation, or continue until you have calculated each of the 12 months without finding condensation in the building component. The starting month is the first month where condensation has been found, i.e. with the previous month without condensation.
 - b. If condensation occur in this calculation, make the same calculation for the previous month, and the previous until you either have found that condensations will occur in each of the 12 months in which case it does not matter which month is chosen as the starting month, or that you find a month without condensation in which case, the following month is the starting month.
2. Calculate moisture accumulation in the starting month.
3. Use Glaser's method to calculate vapour pressure and possible dew points in the following month. The vapour pressure in the interface between layers in which moisture has accumulated is set equal to the saturation vapour pressure.

4. If dew points again are present in this month, the accumulated moisture is calculated and added to a total from the previous month(s). Drying out is calculated in a similar way and is deducted from the total accumulated moisture. If this is negative it is set to zero.
5. Part 3 and 4 are repeated for all remaining months of the year.

Figure 18 shows a vapour pressure curve with and without consideration of the moisture accumulation from the previous month. Vapour pressure before the correction is a straight line (the dotted line) not intersecting the saturation vapour pressure. The corrected vapour pressure (the solid line) is unit linear forced to be at saturation in the interface with accumulated moisture from previous month(s).

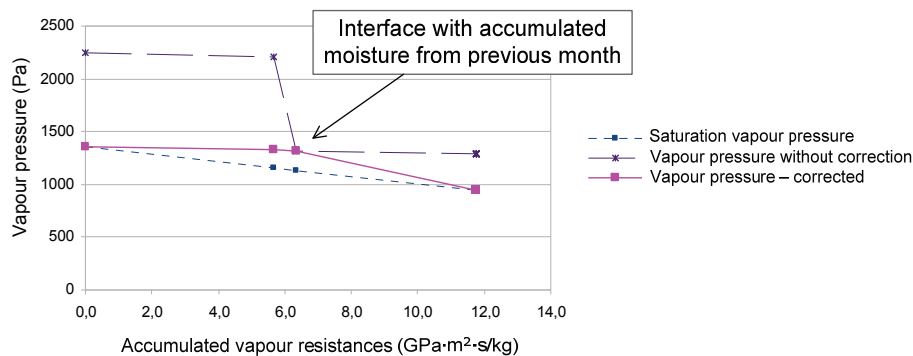


Figure 18. Moisture accumulation. Vapour pressure before and after correction and saturation vapour pressure. Vapour pressure before the correction is a straight line and the adjusted vapour pressure is unit linear where the vapour pressure is equal to saturation vapour pressure in the interface with accumulated moisture.

The calculation will show that there will be a negative moisture accumulation equivalent to a portion of the total amount of moisture drying up. The slope of the line drawn with the x-axis as vapour resistance and y-axis as vapour pressure is a measure of the amount of moisture transported to or from the point. Since the slope before the dew point is smaller than the slope after the dew point, less moisture will be transported to the condensation point than is being transported from the point and thus causing drying out.

In comparison with the estimates of moisture accumulation and drying out in Section 10.1, the brick cavity wall calculated for all 12 months with weather data as monthly averages of the Danish town Ødum will have a total moisture accumulation of less than 0.15 per kg/m² pr year, see Figure 19.

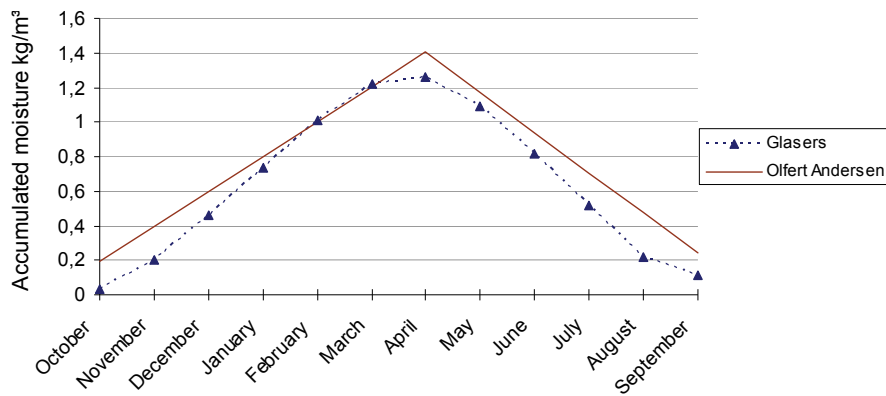


Figure 19. Accumulated moisture for a brick cavity wall. The solid line corresponds to estimate with the maximum level at the beginning of May and linear accumulation before and after. The dotted line is equivalent to 12 months average estimates from Appendix G with accumulated moisture and drying out.

11. References and useful links

- DS/EN ISO 13788:2001 – Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods
- DS/EN ISO 10456:2008 – Building materials and products – Hygrothermal properties – Tabulated design values and procedures for determining declared and design thermal values
- Danish Building Regulation 2008
http://www.ebst.dk/file/17044/Bygningsreglementet_englesk.pdf
- Moisture Analysis – spreadsheet for Glaser’s steady-state diffusion model. Interstitial condensation and internal surface humidity.
<http://personale.vitusbering.dk/sva/Course/Moisture/Calculation/MoistureAnalysis.xls>
- Moisture – Special course for the Building Architects, VIA University, Horsens
<http://personale.vitusbering.dk/sva/Course/Moisture/>
- BuildDesk
<http://www.builddesk.co.uk/>
- MATCH-BOX - Simulation of Moisture Transport in Building Constructions
<http://www.match-box.dk/dk/hvaderbeskrivelse.htm>
- How Humidity is Expressed
<http://daphne.palomar.edu/jthorngren/measures.htm>
- Measuring Humidity
<http://www.bom.gov.au/lam/humiditycalc.shtml>
- Moisture Control in Buildings: Putting Building Science in Green Building
http://www.shelterecology.com/articles/art_Moisture.html
- Mould and Moisture Dynamics
<http://www.wbdg.org/resources/moisturedynamics.php>
- Indoor Air Quality and Mould Prevention of the Building Envelope
http://www.wbdg.org/resources/env_iaq.php
- Glaser method, moisture profile method, dew point method - Essay summary
<http://alcor.concordia.ca/~raojw/crd/essay/essay000090.html>
- Understanding Vapour Barriers
http://www.buildingscience.com/documents/digests/bsd-106-understanding-vapor-barriers/?full_view=1

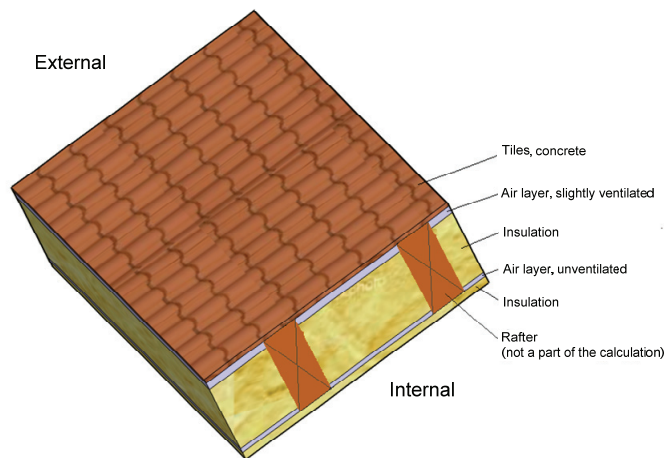
References and useful links (in Danish)

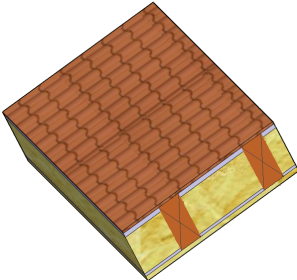
- Bygningers fugtisolering, SBI-178 (in Danish), Andersen, Christensen & Nielsen, 1993
- DMI weather data 1961-1990 (in Danish)
<http://www.dmi.dk/dmi/tr99-5.pdf>

Appendix A. Example: Roof structure without vapour barrier

t_e	= -0,4 °C	External temperature (average for January in Ødum 1961-1990)
φ_e	= 91%	External relative humidity (average for January in Ødum 1961-1990)
t_i	= 20 °C	Internal temperature
φ_i	= 61,1%	Internal relative humidity (from moisture class 3)

The building component is a rafter roof structure with insulation between the rafters. For moisture calculation purposes, the building component consist of (from external) concrete tiles, a slightly ventilated cavity, insulation, an unventilated cavity and again insulation. Data for thermal conductivity and permeability is shown in the table. Text and data in italics (and yellow background) is input into the calculation.



	Material layer thickness, t (m)	Thermal conductivity, λ (W/(m·K))	Thermal resistance, R (m ² ·K/W)	Temperature, t (°C)	Saturation vapour pressure, P _m (Pa)	Permeability, d (kg/(m·s·GPa))	Vapour resistance, Z (GPa·m ² ·s/kg)	Vapour pressure without correction (Pa)	Vapour pressure adjusted, P (Pa)	φ (%)
Internal air				20,0	2337			1428	1428	61,1%
Internal surface			0,25	19,5	2263			1428	1428	63%
Mineral wool	0,050	0,038	1,32	16,7	1900	0,139	0,360	1399	1312	69%
Unventilated cavity	0,015	0,625	0,02	16,6	1893	0,190	0,079	1393	1286	68%
Mineral wool	0,295	0,037	7,97	-0,2	601	0,139	2,122	1224	601	100%
slightly ventilated cavity	0,050	1,111	0,05	-0,3	597	0,190	0,263	1203	597	100%
Tiles, concrete	0,025	1,500	0,02	-0,3	595	0,003	8,333	538	538	90%
External air			0,04	-0,4	591			538	538	91%

Condens
Condens

ΣR 9,66

ΣZ 11,157

ΔP 891

ΣZ_i 2,561

ΔP_i 827

ΣZ_e 8,333

ΔP_e 59

The table also shows that there will be dew points at two interfaces, namely interfaces between mineral wool and the slightly ventilated cavities and between the slightly ventilated cavity and tiles.

Graphical overview of the example:

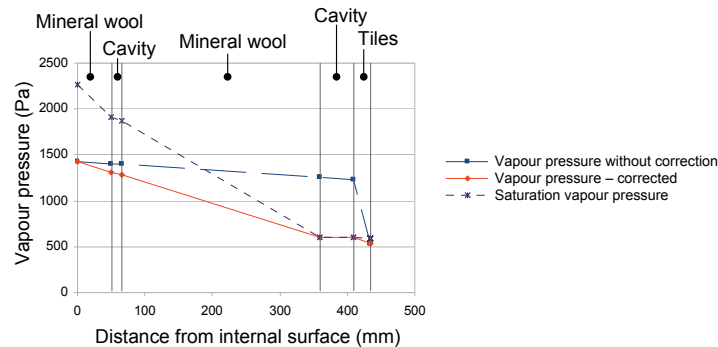


Figure 20. Vapour pressure before and after correction and saturation vapour pressure for a roof structure.

Dew points will occur at the interfaces between layers of mineral wool and cavity and interface between the cavity and tile. This is marked by the solid line describing the vapour pressure after correction. The vapour pressure and saturation vapour pressure are identical in these two interfaces.

Figure 21 has accumulated vapour resistances as the x-axis giving the vapour pressure curve before the correction as a straight line. The corrected vapour pressure curve is linear before the first dew point, between the dew points following the saturation curve and again after the dew has ended, i.e. the curve consists of three straight line segments.

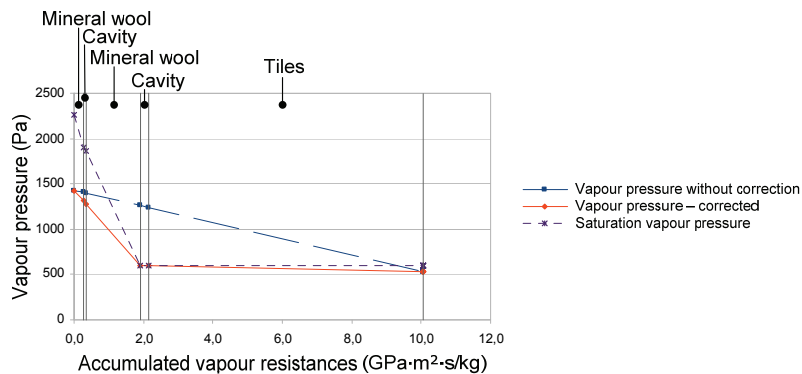


Figure 21. Vapour pressure before and after correction and saturation vapour pressure for a roof structure. Accumulated vapour resistances are chosen as the x-axis.

A calculation of the required Z-value with the formulas from chapter 7 shows that $Z_{necessary} = 109 \text{ GPa}\cdot\text{m}^2\cdot\text{s}/\text{kg}$

Assuming this calculation with the given parameters of temperature and relative humidity represents the critical month, the building component can be made condense free by inserting a vapour barrier

with a Z-value of at least $109 \text{ GPa}\cdot\text{m}^2\cdot\text{s}/\text{kg}$. For example, a 0.15 mm Polyethylene with a vapour resistance at $375 \text{ GPa}\cdot\text{m}^2\cdot\text{s}/\text{kg}$ located on the warm side of the large insulating layer.

Doing this, a new calculation with the same data for temperature and relative humidity provides a vapour pressure distribution as shown in Figure 22 below.

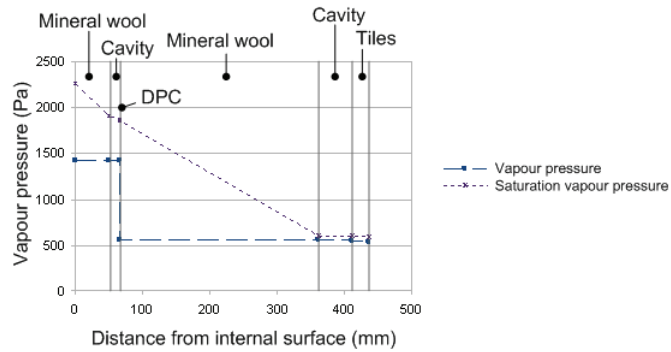


Figure 22. Vapour pressure before and after correction and saturation vapour pressure for a roof structure with a vapour barrier (DPC) inserted

Appendix B. Exercises

B.1. General questions

- 1) Why is it beneficial to know the dew point temperature for internal air?
- 2) Explain, using the vapour diagram, why it is worth venting on a winter's day even if the external relative humidity is higher than the internal, maybe at 100% RH
- 3) Explain also, using the vapour diagram, how venting could be carried out.
- 4) What is the difference between absolute humidity and relative humidity?
- 5) Why is relative humidity an important measurement?
- 6) When and where could mould grow be a problem?
- 7) What are the best living conditions for dust mites?
- 8) What are the best living conditions for mould grow?
- 9) How would you determine the internal relative humidity?
- 10) How could you keep the internal relative humidity to an acceptable value?
- 11) What should be the value of the relative humidity on an internal surface?
- 12) Which moisture transport mechanisms do you know?
- 13) How can you graphically determine any dew points in a building component?
- 14) How can you (graphically) determine the amount of moisture accumulation in a building component
- 15) What are the limitations of the Glaser's steady-state model – the model used in the spread sheet MoistureAnalysis.xls and in BuildDesk?
- 16) Which measures can be taken if you would find in your calculation that a building component accumulates moisture?
- 17) How could you dry out wet materials and structures before moving in?
- 18) The building permit may impose requirements for a documentation provided by a structural damp specialist – what do you think this documentation may include?

B.2. Water vapour diagram

- 1) How much water can be contained in 1 m³ of air at 14 °C?
- 2) If the temperature is decreased to 6 °C, how many grams are released per m³ of air?
- 3) A soft drink is taken from the refrigerator at 5 °C. The bottle is damp (just forming condensation). The room temperature is 18 °C, what is the relative humidity in the room?
- 4) The room temperature is 20 °C and relative humidity is 60%. How much can the temperature be decreased before the dew point is reached?
- 5) An un-insulated cold water pipe with temperature 8 °C is in a room with a relative humidity of 45%. If condensation forms on the pipe, what is the room temperature?
- 6) The room temperature is decreased to 15 °C, still with a relative humidity of 45%. Will condensation now form on the pipe?
- 7) If condensation had formed on the pipe, what would the water temperature in the pipe have been?

B.3. Dew Point Calculation

- 1) Make a graphical determination of any dew points for the brick cavity wall with material data given in the table at page 17. Use internal condition $t_i = 20^\circ\text{C}$ and $\phi_i = 60\%$ and external condition $t_e = 3^\circ\text{C}$ and $\phi_e = 90\%$
 - a. Draw the straight line temperature curve as shown in Figure 11 at page 12 with the conditions $t_i = 20^\circ\text{C}$ and $t_e = 3^\circ\text{C}$. Show the interfaces between the layers
 - b. Read temperatures in each interface and convert these to saturation vapour pressure using the second chart at Appendix C page 32
 - c. Find the vapour pressure both for internal condition $t_i = 20^\circ\text{C}$ and $\phi_i = 60\%$ and for external condition $t_e = 3^\circ\text{C}$ and $\phi_e = 90\%$ using the second chart at Appendix C and draw the straight line vapour pressure curve as shown in Figure 12 at page 12
 - d. Draw the saturation vapour pressure determined under b in the same chart as in c.
 - e. Determine whether the two curves intersect each other, as this indicates a dew point
- 2) Use a spreadsheet (e.g. "MoistureAnalysis.xls") for the brick cavity wall. Use the material data from the table in Section 9.1 and weather data as an average of months from October to April in Ødum, i.e., external temperature of $t_e = 2.9^\circ\text{C}$ and relative humidity of $\phi_e = 87\%$, and internal temperature of $t_i = 20^\circ\text{C}$ and relative humidity of $\phi_i = 60.6\%$ (moisture class 3). What can you see from the table, graphs and moisture accumulation? Compare the solution to the graphical determination in question 1 above.
- 3) It appeared that the brick cavity wall would accumulate moisture during the heating period and this is not entirely dried up during the summer months. If we would use the Danish moisture class 2, which also covers dwellings with low occupancy, will this calculation show accumulated moisture or will this dry out during the summer period?
- 4) Use a spreadsheet (e.g. "MoistureAnalysis.xls") to calculate any dew points, critical surface humidity and moisture accumulation in a cavity wall, which consists of 108 mm brickwork, 100 mm aerated concrete and 100 mm mineral wool in the cavity, see Figure 23. Use weather data from Ødum for external temperature and relative humidity, see Appendix G and humidity class 3 including dwellings with low occupancy.

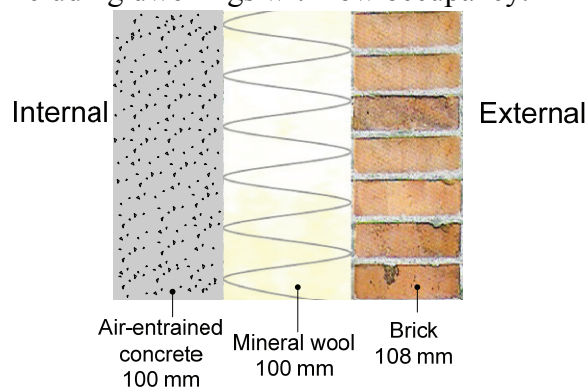
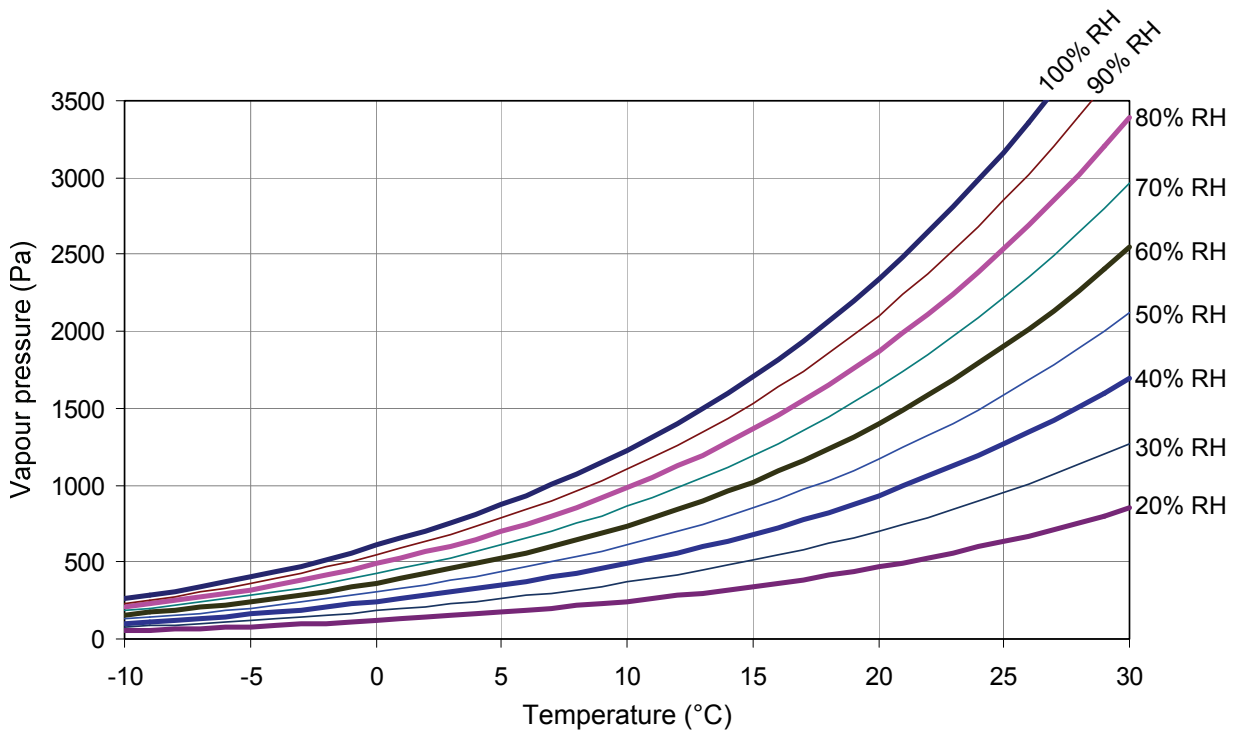
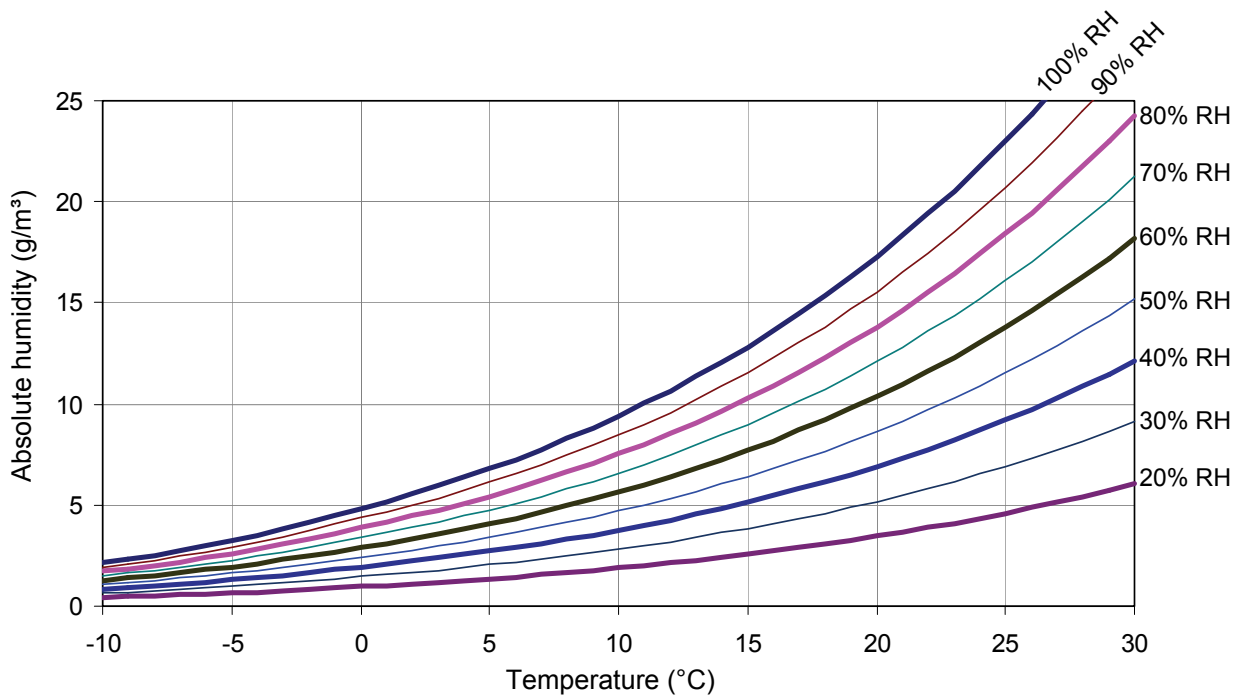


Figure 23. External cavity wall with aerated concrete, mineral wool and brick

- 5) Replace the aerated concrete with a concrete element with thermal conductivity $\lambda = 1,0 \text{ W}/(\text{m}\cdot\text{K})$ and permeability $d = 0,008 \text{ kg}/(\text{GPa}\cdot\text{m}\cdot\text{s})$ and make a new calculation. Do the calculation now show any condensations risk?

Appendix C. Water vapour diagram



Appendix D. Water vapour tables and analytical expressions

The formulas and diagrams are empirically determined; see DS/EN ISO 13788.

t (°C)	P _{sat} (Pa)	c (g/m ³)
-10	259,3	2,14
-9	283,4	2,33
-8	309,4	2,53
-7	337,6	2,75
-6	368,2	2,99
-5	401,2	3,24
-4	436,9	3,52
-3	475,5	3,82
-2	517,1	4,13
-1	562,0	4,48
0	610,5	4,85
1	656,4	5,19
2	705,3	5,56
3	757,4	5,95
4	812,8	6,36
5	871,9	6,80
6	934,6	7,26
7	1001,3	7,75
8	1072,2	8,27
9	1147,5	8,82
10	1227,3	9,40

t (°C)	P _{sat} (Pa)	c (g/m ³)
11	1312,0	10,01
12	1401,8	10,66
13	1497,0	11,34
14	1597,7	12,06
15	1704,4	12,82
16	1817,3	13,63
17	1936,6	14,47
18	2062,8	15,36
19	2196,2	16,30
20	2337,0	17,28
21	2485,6	18,32
22	2642,4	19,41
23	2807,8	20,55
24	2982,2	21,76
25	3165,9	23,02
26	3359,5	24,35
27	3563,2	25,74
28	3777,7	27,19
29	4003,3	28,72
30	4240,5	30,33

$$P_{sat}(t) = 610,5 \cdot e^{21,875t/(265,5+t)} \quad (\text{when } t < 0)$$

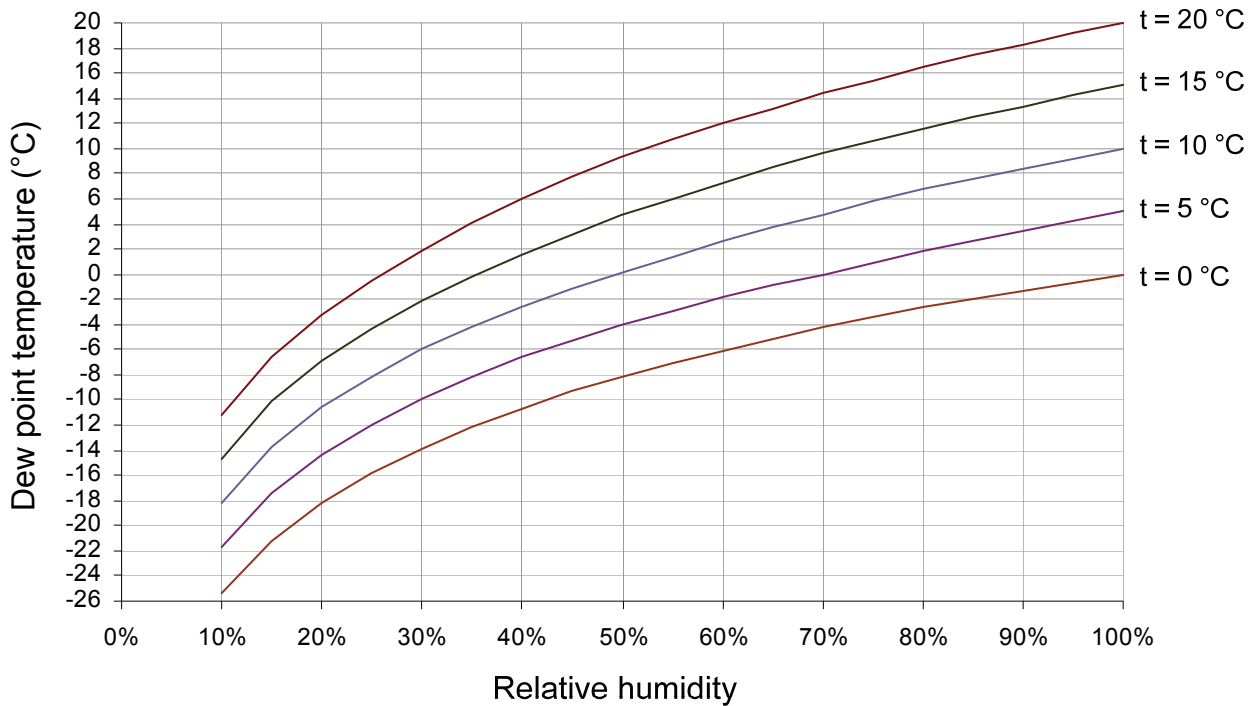
$$P_{sat}(t) = 610,5 \cdot e^{17,269t/(237,3+t)} \quad (\text{when } t \geq 0)$$

$$t(P_{sat}) = \frac{265,5 \cdot \ln(P_{sat} / 610,5)}{21,875 - \ln(P_{sat} / 610,5)} \quad (\text{when } P_{sat} < 610,5)$$

$$t(P_{sat}) = \frac{237,3 \cdot \ln(P_{sat} / 610,5)}{17,269 - \ln(P_{sat} / 610,5)} \quad (\text{when } P_{sat} \geq 610,5)$$

$$c(t) = \frac{P_{sat}}{461,5 \cdot (273 + t)}$$

Appendix E. Dew point temperature



Analytical calculation of dew point temperature:

- Determine the temperature t , and the relative humidity ϕ
- Calculate the saturation vapour pressure for the given temperature $P_{\text{sat}}(t)$ using the formula in Appendix D
- Calculate the vapour pressure as $P = \phi \cdot P_{\text{sat}}(t)$ – this corresponds to the saturation vapour pressure of the dew point temperature $P_{\text{sat}}(t_{\text{dew}})$
- Calculate the dew point temperature from the vapour pressure, $t_{\text{dew}}(P)$ using the formula in Appendix D

Appendix F. Material data

Material	Thermal conductivity, λ W/(m·K)	Permeability, d kg/(m·s·Gpa)
Acrylic	0,2	0,000019
Air, unventilated	0,625	0,19
Air, slightly ventilated	1,111	0,19
Brick, external leaf	0,78	0,020
Brick, internal leaf	0,67	0,019
Carpet / textile flooring	0,06	0,038
Cement, sand	1	0,019 - 0,0316667
Clay	1	0,00475 - 0,0063333
Clay, silt	1,5	0,0038
Concrete	0,8-1,7	0,0019 - 0,003
Concrete, air-entrained	0,22	0,021
Concrete tiles	1,5	0,003
Elastomeric foam, flexible	0,05	0,000019
Gypsum	0,18	0,019 - 0,0475
Gypsum plasterboard	0,25	0,0048
Lime, sand	0,8	0,019 - 0,0316667
Limestone	1,1 - 2,3	0,001 - 0,005
Linoleum	0,17	0,0002
Mineral wool	0,037-0,042	0,125-0,19
Natural pumice	0,12	0,02375 - 0,0316667
Plastic	0,25	0,000019
Polyethylene foam	0,05	0,0019
Polyurethane (PU) foam	0,05	0,0031667
Polyvinylchloride (PVC)	0,17	0,0000038
Sand and gravel	2	0,0038
Sandstone (silica)	2,3	0,00475 - 0,0063333
Silicone foam	0,12	0,000019
Silicone, filled	0,5	0,000038
Silicone, pure	0,35	0,000038
Plywood	0,13	0,0027
Timber	0,12-0,18	0,0038 - 0,0095
Underlay, cellular rubber or plastic	0,1	0,000019
Underlay, felt	0,05	0,0095 - 0,0126667
Underlay, wool	0,06	0,0095 - 0,0126667

Material	Thermal conductivity, λ W/(m·K)	Vapour resistance, Z GPa·m ² ·s/kg
Aluminium foil 0,05 mm	0,25	7895
Aluminium paper 0,4 mm	0,25	52,6
Bituminous paper 0,1 mm	0,17	10,5
Breather membrane	0,17	1,053
Paint -emulsion	0,17	0,526
Paint -gloss	0,17	15,79
PE foil (stapled) 0,15 mm	0,17	42,1
Polyethylene 0,15 mm	0,17	263
Polyethylene 0,25 mm	0,17	526
PVC foil	0,17	158
Vinyl wallpaper	0,17	10,5

Appendix G. DMI weather data for Ødum 1961-1990

Weather Data is taken from the Danish DMI report <http://www.dmi.dk/dmi/tr99-5.pdf> in which data for a number of other stations in Denmark can be found.

month	Temperature t_e (°C)	Relative humidity φ_e (%)
January	-0,4	91,0%
February	-0,5	90,0%
March	1,8	86,0%
April	5,5	77,0%
May	10,7	73,0%
June	14,0	75,0%
July	15,1	76,0%
August	15,1	76,0%
September	12,0	82,0%
October	8,5	86,0%
November	4,2	89,0%
December	1,2	91,0%
Annual mean	7,3	82,7%
Mean for October- April	2,9	87,1%