Tipping point for condensation water drainage on surfaces and interfaces of insulated wall assemblies – experimental method to define water content limits for hygrothermal simulation models.

Hartwig Michael Kuenzel[1], Eri Tanaka[2], Daniel Maria Zirkelbach3
Fraunhofer IBP
1. ORCID: 0000-0001-8305-0262, hartwig.kuenzel@ibp.fraunhofer.de; 2. ORCID: 0009-0006-2336-7106, eri.tanaka@ibp.fraunhofer.de; 3. ORCID: 0000-0001-8251-5910, daniel.zirkelbach@ibp.fraunhofer.de

Abstract: If condensation occurs on non-hygroscopic surfaces of insulated wall constructions, droplet runoff may happen if the amount of condensate exceeds certain limits. Depending on the situation this phenomenon may help to dry the wall, but it may also result in material degradation by water accumulating at the bottom where drainage is not intended. The limits for interstitial condensation amounts on non-hygroscopic materials calculated by the dew-point method in European standards differ with values up to 500 g/m². However, it is questionable whether these limits are based on rigorous experiments and whether they are suitable to evaluate hygrothermal simulation results. Therefore, a laboratory test method has been developed to determine the amount of condensate required for water to run off from vertical surfaces or interfaces of insulated assemblies. For this test 14 fibrous insulation materials (9 x mineral wool, 3 x wood fibre, 2 x cellulose) and 4 types of condensation planes (hydrophilic, hydrophobic, smooth, or rough surface) were examined. The results proved to be much lower than in the above-mentioned standards. Mostly, they ranged between 100 and 200 g/m². Furthermore, by correlating the acceptable amount of condensate with the hygrothermal properties of the insulation materials, a simple formula was derived to estimate the material specific limit value, using its moisture equilibrium at 80 % RH. Finally, by comparing the test results with hygrothermal simulation results, it can be concluded that the water content in the critical one-centimetre-thick layer of the assembly, referred to in DIN4108-3 (2018), is appropriate to assess the probability of condensate runoff.

Keywords: Interstitial condensation, condensate runoff, hygrothermal simulation, fibrous insulation.

1. Introduction

The application of hygrothermal simulation tools for moisture control assessment and design have become more widespread in the past three decades. Today, many national and international moisture control standards and guidelines refer to these tools as being the most reliable way to assess the dynamic moisture performance of building envelope components, because they consider hygrothermal inertia as well as vapour and liquid transfer. The most common of the hygrothermal simulation tools have been extensively experimentally validated. Mostly, this has been done by comparing measured and simulated parameters, such as water content, relative humidity (RH) and temperature, at certain positions within the building assembly at defined timesteps. While most

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 666 - 679.

building materials are porous and absorb water, there are also material layers that absorb very little water or no water, respectively vapour. Examples are plastic foams or films as well as metal sheets or foils. If their surface temperature drops below the ambient dewpoint, condensation will occur in form of small droplets. When the droplets become more numerous and grow larger, there is a chance of water runoff if the amount of condensate exceeds the surface water retention capacity of the specific layer.

This is a well-known fact and may be intended to drain condensate off the surface. However, if there are no provisions to collect or discharge the water, it may accumulate somewhere in the construction and cause damage. In that case, the occurrence of condensation should be limited by vapour control measures to remain below the tipping-point of condensate runoff. Since hygrothermal simulation tools can predict the amount of condensate on non-water absorbing material layers, knowing the water retention capacity of such layers helps to prevent the risk of runoff. Looking at the steady-state vapour diffusion standards in Europe, proves that there is no real consensus on limiting the amount of condensate on non-water absorbing surfaces. The German moisture control standard DIN 4108-3 (2018) specifies a maximum of 500 g/m² and the ISO EN Standard 13788 (2012) warns that more than 200 g/m² bears the risk of runoff. The British Standard BS 5250:2011+A1:2026 contains a table that states even lower limits: Droplets form and begin to run down vertical surfaces between 30 and 50 g/m² of condensate. This is a pretty large range for assessing the risk of condensate runoff. Therefore, the aim of this paper is to establish limit values for hygrothermal simulation analyses that are realistic and take into account the roughness and installation specifics of the material surface/interface in question.

2. Condensation tests

There are numerous studies on the drainage of rainwater on cladding systems or water resistive barriers, (e.g. Straube 2007). However, the authors believe that their results may not be transferable to condensate runoff because field tests of Künzel (2007) identified large differences in the water retention properties of external wall coatings depending on the type of moisture load. While rainwater was repelled form hydrophobic surface coatings and drained immediately, condensate forming very small droplets still adhered to the water repellent surface. From this finding, it may be concluded that experiments looking at the drainage of driving rain or spray water may show different results from those exploring the drainage of water condensing on a surface. Therefore, the following experiments have been designed to study condensate runoff exclusively.

Because there is often confusion about the hygrothermal characteristics of materials and material layers, this paper makes a clear distinction between liquid water absorption and hygroscopic vapour sorption. Liquid water absorption due to capillary action happens only in hydrophilic materials. Hydrophobic materials may have similar pore structures, but they don’t absorb liquid water because water will not spread on their surfaces (surface angle of droplets > 90°). Hydrophobic materials may still be hygroscopic, which means they can adsorb water molecules at their interior surfaces.

2.1. Test unit

The test is carried out in an air-conditioned room (constant 23 °C and 65 % RH, dew point 16.1 °C). In this room, a cooling plate (30 cm x 30 cm) is placed vertically, and its surface temperature is controlled to the set temperature by a cryostat cooling circuit. The investigated material is placed in a rectangular, laterally insulated, frame (10 cm x 10 cm with the thickness of 2 cm). The heat conducting metal backside of this frame is placed against the cooled plate with heat conducting paste. In a preliminary test, the cooling plate has been chilled by cryostat with its setpoints between 2 and 7 °C. Significant differences in condensation and runoff patterns due to the temperature dependent viscosity of water or the intensity of condensation could not be detected.

Therefore, all further experiments were carried out with the chilled surface controlled with the set-temperature of cryostat at 2 °C. The surface temperature was about 4 - 7 K warmer than the set temperature depending on the test material. In total, four frames are placed on the cooling plate (see Figure 1, left). The foam insulation of the frames helps to avoid thermal bridges at the edge of each frame. On the chilled surface of the metal plate, the surface materials to be investigate can be attached (Figure 1, right). Afterwards, the cavity may be filled with fibrous insulation material which is held in place by rubber bands to ensure direct contact with the surface. The drained condensate is collected in a small vessel under each frame (not shown).

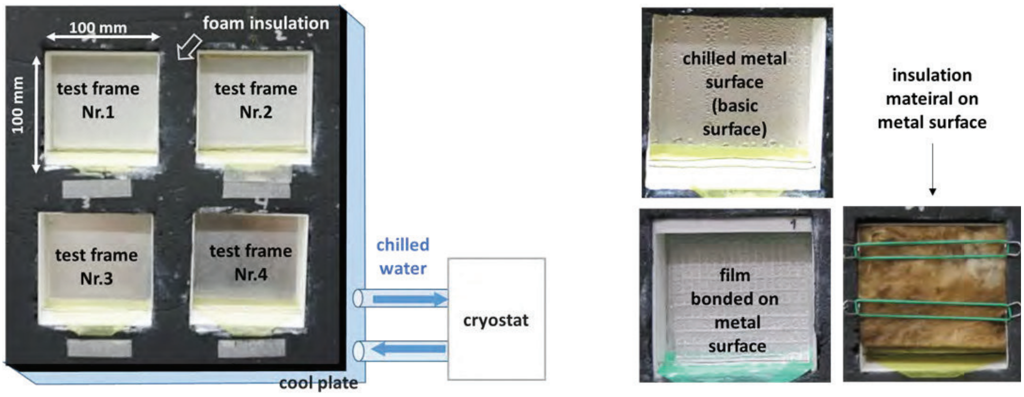


Figure 35: Left: Condensation test unit. Four frames with a metal backside are fixed with heat-conducting paste to a cooled surface. Each frame is surrounded by foam insulation material. Right: Frame with test material. The default surface is a metal plate, on which a film or an insulation material is placed.

2.2 Water retention capacity of surface layers

The condensate remaining on the surface of the substrate is blotted by an absorptive paper, and the weight difference of the paper before and after blotting indicates the amount of retained surface condensation. This amount is divided by the area of the tested material. At first, the amount of condensate adhering to different surface materials and textures is determined separately (without contact to any insulation material). The following four surface materials with different hydrophobicity and roughness are examined and shown in Figure 2.:

- metal (hydrophilic)
- PE film (hydrophobic, smooth)
- film laminated on fleece (hydrophobic, fine structured)
- film reinforced with fabric (hydrophobic, coarse structured)

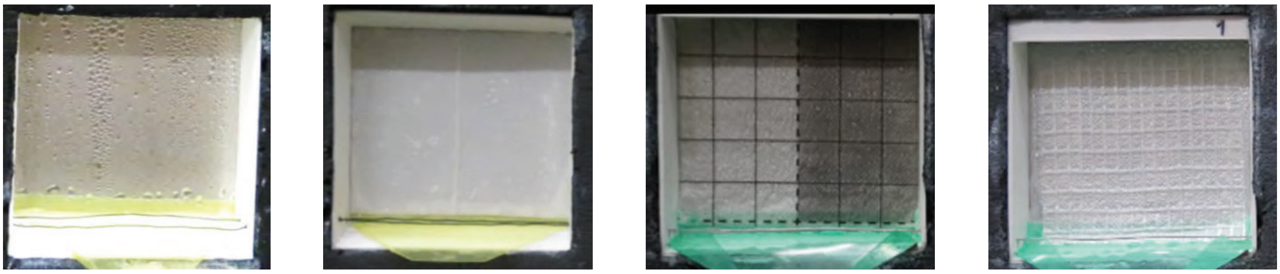


Figure 36: Tested surface samples from left to right: metal (hydrophilic), PE film (hydrophobic, smooth), film laminated on fleece (hydrophobic, fine structured), film reinforced with fabric (hydrophobic, coarse structured).

As described above, the set temperature of the cryostat and the test duration was varied. As no clear correlation between each of these two factors (temperature and duration) and measured water retention can be established, all measured values are used to evaluate the results and presented as a box plot in Figure 3 . The amounts of water clinging to the surface clearly differ with the surface properties. The hydrophilic metal plate retains more condensate than the hydrophobic PE-film. Increasing the roughness of a hydrophobic surface also leads to a higher condensate retention capacity.

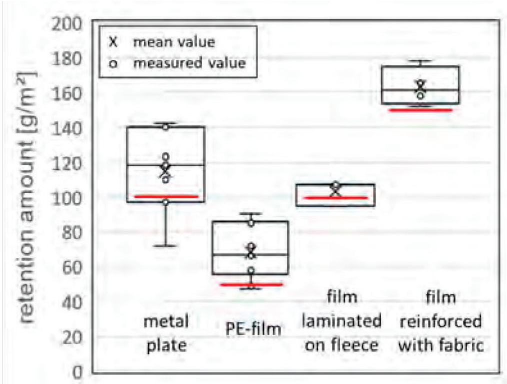


Figure 37: Measured amounts of condensate on four types of surfaces when runoff had started. The boxplot shows the variations of the results, and the red lines indicate the limit values defined in Table 1.

Based on the experimental results described above, a limit value of the condensate retention capacity on each surface is determined and listed in Table 1. These values are for each case below the mean values of all measured retention values on a surface at all temperatures and test durations. It should be noted that the determined retention amounts are lower than the maximum possible level because condensate runoff had already occurred prior to the blotting test. Thus, the obtained amounts of condensate still clinging to the surface represent limit values that are still on the safe side without being overly conservative. Furthermore, the retention capacity on the hydrophobic film laminated on fleece of 100 [g/m²] matches well with the results of Janssens (1998).

Table 18: Limit value of retention amount according to substrate property, determined as minimum of several tests, thus representing limits on the safe side concerning the risk of condensate runoff.

Substrate characteristic	hydrophilic	hydrophobic		
		smooth	fine structured	coarse structured
Investigated substrate	Metal	PE-film	Film laminated on fleece	Film reinforced with fabric
Limit value [g/m³]	100	50	100	150

2.3 Water retention capacity at insulated interfaces

In the next step, the retention capacities for condensate on cold surfaces in contact with 14 different insulation materials are investigated. Table 2 lists the insulation materials with their relevant properties. As representatives of mineral insulation materials, six glass wool variants with bulk densities between 20 and 65 kg/m³ and, three stone wool samples with higher bulk density (111 to 135 kg/m³) are selected. One glass wool and one stone wool product (glass wool #3 and stone wool #2) is exceptionally hydrophilic and, thus, absorbs liquid water, while the others are hydrophobic. As cellulose insulation, a standard product and a hydrophobic product are selected. The tested wood fibre insulation samples represent the variety the most common bio-based building insulation products in Germany. Wood fibre sample #1 is a flexible insulation batt with a density of 60 kg/m³, generally used for cavity insulation. The other two wood fibre samples are rigid insulation boards used as exterior cavity sheathing or external insulation. Their density is higher than the density of cavity insulation materials and they are supposed to be non-water absorbing. This means they repel liquid water but can still adsorb vapour which means they are hygroscopic.

Table 19: Tested materials with their material properties

Insulation material	density	moisture equilibrium		free saturation	water absorption coefficient
		80 % RH	97 % RH		
	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m²√h]
glass wool #1	20	0.7	3.8	372	0*
glass wool #2	22	0.9	4.3	335	0*
glass wool #3	22	n.d.	n.d.	n.d.	5.3
glass wool #4	30	1.1	5.7	510	0*
glass wool #5	35	0.8	3.9	536	0*
glass wool #6	65	n.d.	n.d.	n.d.	0*
stone wool #1	111	0.75	1.4	600	0*
stone wool #2	128	0.9	4.0	929	18.0
stone wool #3	135	0.6	2.0	121	0*
cellulose fibre #1	50	3.7	14.7	173	0*
cellulose fibre #2	50	7.9	20.1	614	12.0
wood fibre #1	60	7.7	48	307	9
wood fibre #2	140	16	35	570	0.14
wood fibre #3	96	10.5	22.3	464	0.2

n.d.: no data, *: hydrophobic

The insulation materials are installed in close contact with the substrate on the cold surface as shown in Figure 4. Loose cellulose is filled into the frame in the amount equivalent to the installation density of 50 kg/m³ and held in place with a fine stainless-steel mesh. The other material samples are fixed with a rubber band. The batt insulation product samples are 10% larger than the frame and fixed by two rubber bands to achieve the same close fit as in practice situations. All insulation samples are distanced from the bottom of the frame by two wires to avoid contact with the drained condensate to avoid water absorption at the footing, which could distort the test results.

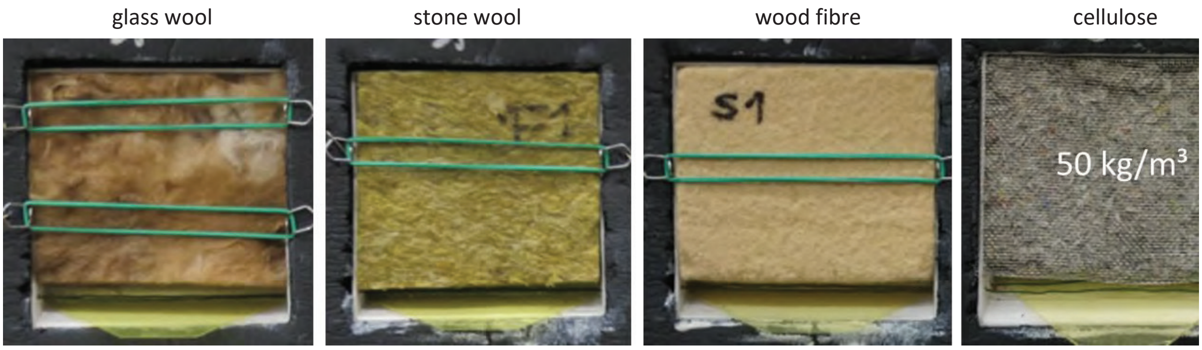


Figure 38: Mounting of insulation materials on condensation test equipment.

To detect the influence of substrates such as films or foils, all insulation samples are combined with two types of substrates, the metal plate (hydrophilic) and the PE film (hydrophobic and smooth structure). Once the drained water is visible in the vessel under each frame, the test frame is removed from the cold plate and the amount of retained condensate is determined. By separating the insulation material from the substrate, it is possible to differentiate between the condensed water in the insulation and the water retained by the PE-film or metal plate. In case of the cellulose fibres only the total amount of condensate can be determined because the fibres could not be removed cleanly from the substrate, as individual fibres would still adhere to the substrate.

Figure 5 shows the measured retention amount on the surfaces (PE film or metal plate) and on or in the materials. In 8 of 14 tested insulation materials, condensation ran off within 24 hours. In the case of two wood fibre materials, condensation ran off between 24 and 48 hours. In the remaining four materials, condensation still did not run off after three days (72 hours). The condensation test was terminated after three days, and the amount of water contained in the samples after this period was determined. Except for glass wool #3, all hydrophilic materials contained more than 1000 g/m² of water in the frame, mostly in the insulation. This indicates that hydrophilic insulation materials may not be comparable to hydrophobic materials in terms of condensate retention and water drainage.

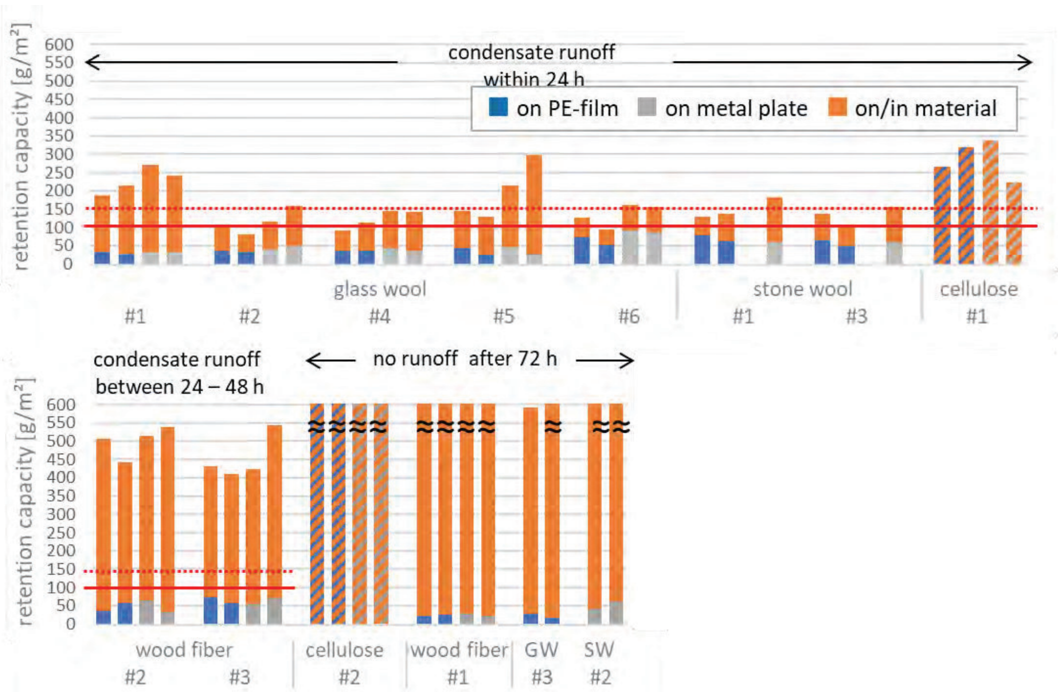


Figure 39: Measured condensate retention on and in the insulation material (orange) and on the PE film (blue) or metal surface (grey). For cellulose these are not differentiable. The red lines at 100 g/m² (solid line) and 150 g/m² (dotted line) refer to the limits defined below.

Regarding the drainage of condensate in insulated cavities closed by a non-water absorbing membrane or sheathing at the cold side, the following can be concluded from the results:

- The current limit value of 200 g/m² according to DIN EN ISO 13788 (2012) appears to be too high for most mineral wool products in the test. Therefore, a lower limit should be introduced here if runoff must be prevented. A safe general limit would be 100 g/m².
- With a hydrophilic surface (metal), the total retention quantity is approx. 150 g/m². The difference of 50 g/m² increase agrees well with the difference of the surface retention capacity without insulation materials.
- Cavities filled with hygroscopic insulation materials seem to buffer a significant part of the vapour diffusion flux. This increases the condensate retention capacity of the building assembly to approx. 500 g/m².

Also the capillary water absorption of the insulation material plays an important role in raising the condensate retention characteristics of insulated cavities. If the water absorption coefficient (A-value) of the insulation material exceeds 5.0 kg/m²√h more than 1000 g/m² of condensate could be retained until the end of the test after 72 hours. However, in our test, only few materials were so hydrophilic.

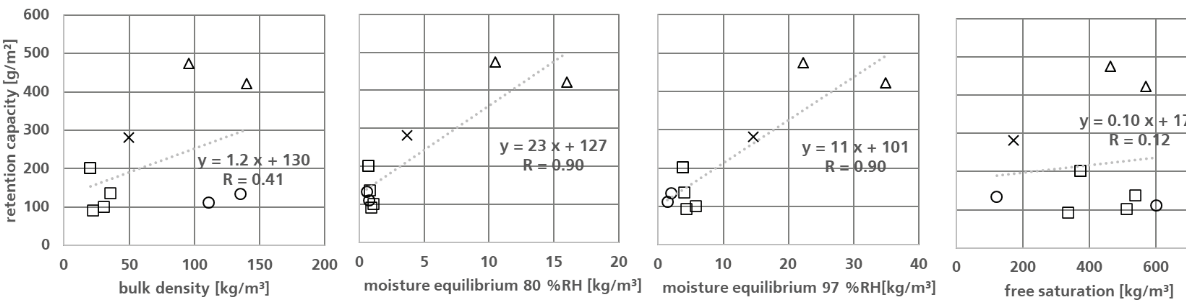
2.4. Essential material properties for the retention capacity of non or weak absorbent insulation materials

The test results indicate that the retention values determined for 10 different hydrophobic insulation materials vary in a wide range from approx. 100 to around 550 g/m². To enable a product-specific and finer evaluation of the condensation runoff risk in addition to the limit value of 100 g/m², which is usually on the safe side, the impact of specific material parameters such as density and hygroscopic vapour sorption on the condensate retention capacity is investigated. Therefore, a correlation analysis is carried out between the retention capacity and bulk density, sorption moisture at 80 % and 97 % RH and at free saturation. The results are shown in Fig. 6 above for the hydrophilic metal plate and below for the hydrophobic PE film, each with a regression line through the measured data. The equations of the regression lines and the respective correlation coefficient R are also given.

The correlation of the retention capacity with the bulk density of the insulation material (Fig. 6 left) is surprisingly low, at only 0.41. Since a higher density indicates a higher number of fibres and thus possibly more "runoff resistance", a stronger influence was expected here. With 0.22 and 0.12 respectively, the correlation of the retention capacity with the free water saturation is even lower and, therefore, this correlation is discarded.

In contrast, a significantly better correlation can be observed between the retention capacity and the sorption moisture both at 80 % RH and 97 % RH. The coefficients here are between close to 0.9 in each case. The sorption moisture level in the higher moisture range thus appears to be the decisive, easily determinable variable that most strongly influences water retention. Since the correlation with the water content at 80 % RH is even slightly higher than at 97 % RH and, moreover, the so-called reference moisture content is known and available for most materials, the following approach uses this correlation.

on PE-film (hydrophobic, smooth)



on metal plate (hydrophilic)

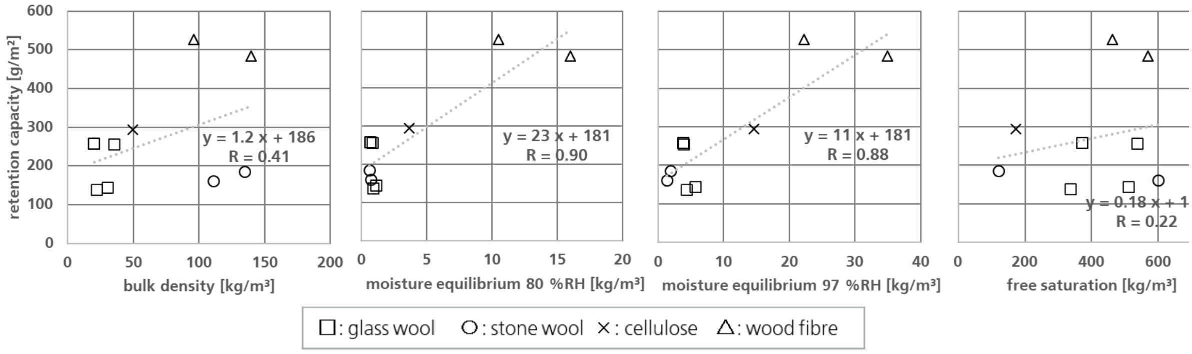


Figure 40: Measured retention amount via material properties (bulk density, free saturation, moisture equilibrium at 80 % and 97 % RH) with regression line and its formula together with correlation coefficient (R). On the left are results examined on metal and on the right on PE foil.

2.5. Interface- and material-specific limit values

With the help of the degrees of regression between retention capacity and reference moisture content u_{80} on metal (hydrophilic) and PE film (hydrophobic, smooth), the empirical correlation to determine the material-specific limit values is defined in such a way that the limit values remain slightly on the safe side compared to the measured data. This results in the following equation for unknown substrate properties.

Retention capacity RC= 20 [mg/kg] x u80 [kg/m³] + 100 [g/m²] (1)

The retention capacity is increased by 20 g/m² for every 1 kg/m³ of additional sorption moisture content at 80 % RH. The base value represents the 100 g/m² always retained regardless of material and substrate properties. For hydrophilic metal substrates, this base value increases to 150 g/m². The difference of 50 g/m² corresponds to the retention quantities determined on free surfaces without insulation material. Figure 7 shows the calculated correlation together with the measured results. The limits are mostly lower and thus slightly on the safe side with the exception of the two glass wool products, where the retention amount is about 10 g/m² lower than the limit curve in each case. However, this seems acceptable in view of the slightly lower values after the start of the runoff.

on PE-film (hydrophobic, smooth) on metal plate (hydrophilic)

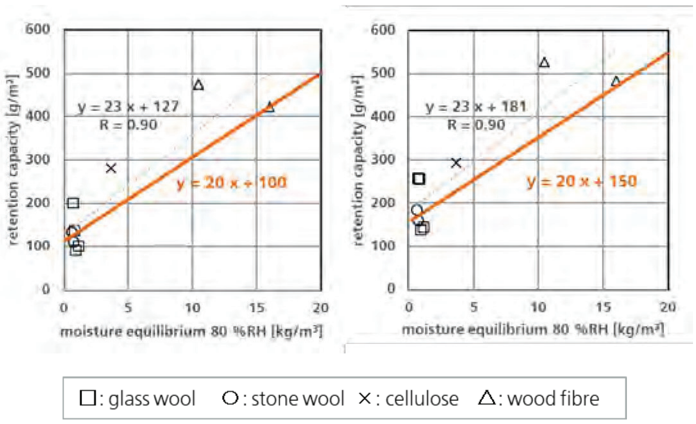


Figure 41: Measured retention capacity plotted over the moisture equilibrium at 80 % RH on hydrophobic and smooth PE film (left) and hydrophilic metal plate (right). The dotted lines represent the regression results, and the orange lines are the resulting limits calculated by equation 2.

It has already been mentioned that the difference in retention capacity on metal and PE film with and without fibre insulation is 50 g/m². In additional tests it could be shown that this correlation also applies for other interface properties. Therefore, the following general equation can be defined:

Retention capacity RC= 20 [mg/kg] x u80 [kg/m³] + b [g/m²] (2)

with:

	100 g/m²	for unknown interface properties
b =	150 g/m²	for hydrophilic or fine structured hydrophobic interfaces
	200 g/m²	for coarse structured (hydrophobic) interfaces

However, an exact classification of the respective surface into the three categories can be difficult in individual cases - for varnished wood, for example, depending on the surface treatment, a coarse or fine texture can be considered. In case of doubt, the value for unknown substrate properties should be selected. If required, the substrate-specific retention capacity can of course also be determined individually in the laboratory.

3. Evaluation by hygrothermal simulation

The laboratory tests are compared to hygrothermal simulation results. The one-dimensional hygrothermal simulation program WUFI® Pro, which has been validated by numerous studies worldwide, is used for the simulation. The boundary conditions are the room air condition (23°C, 65 % RH) and the measured temperature behind the insulation material (approx. 7 °C). The impermeability of the cooling surface is considered by a very high s_d value (s_d = 10000 m). One product of each of the four material types (glass wool, stone wool, cellulose and wood fibre board), for which all required hygrothermal characteristic values are available, is simulated. The total thickness of the insulation layer is consistently 20 mm.

In order to check which choice of the condensation zone thickness is most appropriate, the evaluation of the water content in the insulation layer is carried out for four different condensation zone thicknesses, 1, 5, 10 and 20 mm thickness. This choice means that it takes different lengths of time until the limit value relevant for condensate drainage is exceeded in the respective zone. To simplify the evaluation, it is assumed that all the water in the layer is due to condensation. Since the effect of gravity is not accounted for, the condensate will not run off but stays at the respective position in the building component. Therefore, the risk of runoff must be assessed in a separate step. Fig. 8 shows the increase in the total amount of water in the condensation zones of four different insulation materials, depending on the chosen thickness of the evaluated condensation zone. The retention capacities determined in the laboratory are shown as red lines for the situations on the metal plate and on the PE foil respectively.

For glass and stone wool, the evaluation thicknesses are not relevant to the determination of the time of the first condensation runoff. With the more sorptive materials, cellulose and wood fibres, the curves diverge somewhat further, as not all the water is on the cold side but is stored in larger areas in the material. A too thin evaluation zone would lead to the limit value being exceeded too late here. If an edge layer of only 1 mm thick is evaluated in the hydrophobic cellulose fibre, the water content of this layer exceeds the limit value only after just under 2 days, which contradicts the observation in the laboratory, where condensation had already occurred after 24 hours.

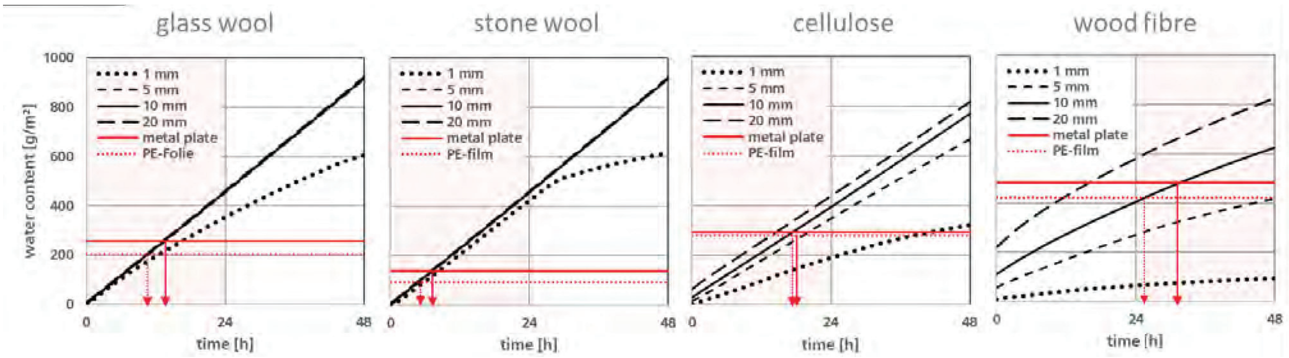


Figure 42: Simulated water content curves in different thicknesses (black) and the measured retention amount (red) on two types of surfaces. Red arrows show the time points at which the water content in a 10 mm layer exceeds the retention amount, i.e. the condensation water is calculated to have run off first time. In the lab test the condensate run off within the time range coloured in red.

When the thicker layers are evaluated, the limit value is exceeded after 14 to 20 hours - i.e. within the time period determined in the laboratory. With wood fibre insulation, the discrepancy between the evaluated layer thicknesses is even more pronounced. If a thin layer of 1 or 5 mm is evaluated, the water content reaches the limit value only after the condensation has run off as determined in the laboratory. In the case of the 2 cm thick layer, on the other hand, the limit value is exceeded too early after about 12-16 hours. In the case of the 1 cm thick layer, the runoff occurs within about 26 to 30 hours, depending on the interface, which is consistent with the laboratory result. Comparable results were also obtained for the other materials not shown.

In summary, the choice of 10 mm for the condensation zone to be evaluated against the condensate runoff limits resulting from the laboratory tests appears to be well suited for evaluating the risk of condensate runoff from hygrothermal simulation results.

4. Conclusions

The results of the condensation tests on vertical non-absorbent surfaces prove that the tipping point for condensate runoff depends on the surface material and its texture as well as on the adjacent insulation material in the cavity. If the condensation plane is not in direct contact with another material, the tipping point is reached at 50 g/m² for smooth polymer surfaces. Smooth metal surfaces and polymer films on fabric can retain up to 100 g/m² and polymer films fortified with a mesh (coarse surface) up to 150 g/m² before runoff occurs. All these values are below the limit of 200 g/m² in EN ISO 13788. According to Straube and Smegal (2007) who conducted drainage test in very small gaps (1 mm), the water being retained in these gaps before run-off occurs can be as low as 25 g/m². However, we didn't not investigate the behaviour of condensate in such small gaps to confirm these finding also for the incidence of interstitial condensation.

If there is no airgap but a hydrophobic fibrous insulation material next to the surface where condensation occurs, the runoff limit for smooth surfaces increases only marginally to about 100 g/m². Generally, condensation on non-water absorbing, non-hygroscopic interfaces of more than 100 g/m² could be chosen as failure criterion if no provisions for safe drainage within the building envelope assembly are provided.

However, this changes if the interface material is hydrophilic or not smooth but having a coarse texture and if the fibre insulation material in contact with the cold interface is hygroscopic or even water absorbing. Hygroscopic materials such as wood fiber or cellulose insulation will slow down or even prevent the process of condensation for a certain period of time by reducing the ambient vapour pressure through vapour absorption. If the material is also absorbing liquid water, it may even wick all the condensate away from the condensation plane. If 100 g/m² is exceeded, the insulation material and substrate properties can be used to check to what extent the limit value is increased in the specific case. The material surcharge is empirically based on the sorption moisture at 80 % RH (u_{80}) via factor 20. As an example, for an insulation material with u_{80} = 2.0 kg/m³, the limit value increases from the base value of 100 g/m² to 140 g/m², irrespective of the substrate properties according to equation (1). In addition, a hydrophilic or coarse textured substrate can further increase the retention capacity by 50 to 100 g/m². This is summarized in equation (2) together with the material dependency. In total, the consideration of the interface and the material type, can increase the limit up to approx. 500 g/m².

To assess the condensation run-off risk at the interface between insulation and external cover layer by hygrothermal simulation, calculation and experimental results were compared. The key factor for a good agreement between calculation and test results is the condensate retention capacity of the insulation layer where condensation actually occurs. A study with varying thickness of the condensation zone in the insulation proved that the choice of a 10 mm thick condensation zone at the exterior end of the insulation layer ensures in the best agreement between calculation and laboratory test results.

5. Acknowledgements

The EnOB project 03ET1649B NaVe was supported by the Federal Ministry of Economic Affairs and Climate Action on the basis of a decision by the German Bundestag.

678 – Tipping point for condensation water drainage on surfaces and interfaces of insulated wall assemblies – experimental method to define water content limits for hygrothermal simulation models.

6. References

BS 5250 (2016) Management of moisture in buildings. Code of practice for control of condensation in buildings; Britisch Standards Institution

Straube, J. (2007) Modeled and Measured Drainage. Storage, and Drying behind Cladding Systems. Proceedings Buildings X, ASHRAE, Atlanta 2007, 11p.

DIN 12087 (2013) Thermal insulating products for building applications – Determination of long term water absorption by immersion; German version EN 12087, Beuth Verlag GmbH, Berlin

DIN 4108-3 (2018) Thermal protection and energy economy in buildings – Part 3: Protection against moisture subject to climate conditions – Requirements, ccalculation methodes and directions for planning and construction, Beuth Verlag GmbH, Berlin

DIN EN ISO 13788 (2012) Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods; German version EN ISO 13788, Beuth Verlag GmbH, Berlin

DIN EN ISO 15148 (2018) Hygrothermal performance of building materials and products - Determination of water absorption coefficient by partial immersion (ISO 15148:2002 + Amd 1:2016); German version EN ISO 15148, Beuth Verlag GmbH, Berlin

Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods German version EN ISO 13788, Beuth Verlag GmbH, Berlin

Janssens, A. (1998) Reliable control of interstitial condensation in lightweight roof systems – Calculation and assessment methods, Diss. K.U.Leuven, Hevertee

Künzel, H.M. (2007) Factors Determining Surface Moisture on External Walls. Proceedings Buildings X Conference, ASHRAE, Atlanta 2007, 6p

Straube, J. & Smegal, J. (2007) The role of small gaps behind wall claddings on drainage and drying. Proceedings 11th Canadian Conference on Building Science and Technology, Banff.