Fraunhofer Institut Bauphysik

Bauaufsichtlich anerkannte Stelle
für Prüfung, Überwachung und
Zertifizierung
Zulassung neuer Baustoffe, Bauteile
und Bauarten
Forschung, Entwicklung,
Demonstration und Beratung auf
den Gebieten der Bauphysik

Institutsleitung
Univ.-Prof. Dr.-Ing. Gerd Hauser
Univ.-Prof. Dr.-Ing. Klaus Sedlbauer

IBP-Report HTB-12/2007

Durability Assessment of Glass Fibre Insulation in Flat Roof Constructions

for
Saint-Gobain Isover

The report contains
11 pages of text
4 Tables
40 Figures

Dipl.-Ing. Daniel Zirkelbach
Dr.-Ing. Hartwig M. Künzel
Dipl.-Ing. Christian Bludau

Holzkirchen, 29. Mai 2007

Head of Department	Group Manager
Dr.-Ing. Hartwig M. Künzel	Dipl.-Ing. Daniel Zirkelbach

Fraunhofer-Institut für Bauphysik
Nobelstraße 12 · D-70569 Stuttgart
Telefon +49 (0) 711/970-00
Telefax +49 (0) 711/970-3395
www.ibp.fraunhofer.de

Institutsteil Holzkirchen
Fraunhoferstr. 10 · D-83626 Valley
Telefon +49 (0) 8024/643-0
Telefax +49 (0) 8024/643-366
www.bauphysik.de

Projektgruppe Kassel
Gottschalkstr. 28a · D-34127 Kassel
Telefon +49 (0) 561/804-1870
Telefax +49 (0) 561/804-3187

1 Introduction and aim of the study

To assess the durability of mineral fibre insulation there are currently several different laboratory tests available, e.g. Nordtest, DUR2 (prEN 14509), Florida test. All these tests have in common that the hygrothermal conditions are rather extreme which often cause durability problems for glass fibre insulation products. While it makes sense to perform tests which allow an acceleration of the natural degradation process, it is also important to ensure that tests do not make products fail that perform well in reality. Therefore the hygrothermal conditions prevailing during these tests should not exceed the temperature and humidity conditions in real life by far. An acceleration of product aging can still be achieved by prolonging the duration of peak loads derived from field tests.

The aim of this study is therefore to determine test conditions that allow an acceleration of the natural aging process without damaging the insulation product in a way that will never occur in reality. The testing conditions have to be backed up by results from field tests and validated hygrothermal simulations to develop the basis for new test methods with more realistic temperature and humidity conditions.

2 Investigations

2.1 Field test

Subject of this study are the measured and simulated hygrothermal conditions in an insulated flat roof with the following composition from inside to outside:

- Load bearing wooden sheathing
- Vapour barrier (aluminium foil, s_d > 1500 m)
- Insulation layer: 90 mm respectively 175 mm glass fibre boards
- Impermeable roofing membrane (elastomer bitumen)

A schematic drawing of the flat roof construction is displayed in Figure 1; the positions of the sensors in a side and a top view are shown in Figure 2. The placement of the sensors at the positions where peak loads are expected has been selected according to preliminary calculations. The temperature measurements are performed by using PT100 temperature sensors. The relative humidity is determined by capacitive sensors. Prior to installation, all sensors are calibrated in the laboratory.

In order to get an extreme scenario with a high initial moisture content it is planned to add about 2 kg/m² of water to the glass fibre insulation. It is expected that this moisture will be trapped in the construction between the vapour barrier and the vapour-tight roofing membrane. With the temperature variations during changing seasons or during a night and day cycle the moisture is expected to migrate between bottom and top of the insulation.

In August 2006 the roof sections with different insulation thickness (90 mm and 175 mm) were set up on the field test site of the Fraunhofer Institute for Building Physics (IBP) in Holzkirchen. Figure 3 displays the IBP field test site with location and orientation of the selected test building. The flat roof sections cover an area of 6.5 m x 6.3 m (approx. 40 m²) each. The test building itself is heated in winter time. This is, however, not sufficient to control the temperature in the attic space under the roof. Therefore, the attic temperature is controlled by electrical wire heating which can be seen beneath the rafters in Figure 4. The rafters are covered by 24 mm strong wooden sheathing boards on which the aluminium vapour barrier is installed (Figure 5).

Before the glass fibre boards can be laid the measuring equipment had to be installed. The interior temperature and humidity sensors are glued directly to the vapour barrier (Figure 6). In the centre of the roof sections the capacitive RH sensor is placed together with a PT100 temperature sensor. At a diagonal distance of approximately 2 m in both directions, two further PT100 are installed one combined with a piece of wood containing moisture pins. The readings of the moisture pins (measurement of electrical resistance) which serve only as back-up for the capacitive sensors will be taken at weekly intervals.

The installation of the insulation layer on top of the continuous vapour barrier is shown in Figure 7. While laying the glass fibre boards the sensors measuring the hygrothermal conditions in the "middle" of the insulation layer are placed sideward in a small cavity of the centre board (Figure 8). Because more severe conditions were expected towards the top of the insulation layer, the vertical sensor position is not exactly in the middle but located about one third of the board's thickness from the top. However, for reasons of simplicity this position will be labelled as "middle" in the following descriptions. Finally, the last sensors are installed on top of the glass fibre boards just below the roofing felt. Figure 9 shows a photograph of the sensors located at the exterior surface of the insulation layer. A closer look at the capacitive humidity sensor with its protecting metal tube located next to the central PT100 sensor is presented in Figure 10. The installation of the back-up moisture sensor (a piece of wood equipped with moisture pins) located next to another PT100 fixed to the surface by adhesive tape is shown in Figure 11.

To raise the initial water content of the insulation layer prior to installation (planned were approx. 2 kg/m²) the glass fibre boards are intermittently subjected to spray-wetting with a garden hose for several hours (Figure 12). The moisture uptake is registered by weighing representative boards before and after this treatment. However, the target moisture is not always attained due to the hydrophobicity of the boards. Another problem is the warm weather during the roof set-up which tends to dry out the boards. Therefore, just before closing the roof with the bituminous felt (the boards are wetted again by using a watering can. In order to prevent any drying of the initial moisture through joints or section interfaces the roofing felt was glued to the vapour barrier at the edges (Figure 13).

As soon as the roof construction works are completed the continuous recording of the data delivered by the installed sensors begins. Figure 14 shows a top view of the completed roof and a photograph from the south façade of the test building where the two roof sections with their differing insulation thickness can be seen. The climatic data necessary for this investigation, such as temperature, solar radiation (direct and diffuse) as well as sky radiation are simultaneously registered by the IBP weather station. To allow a reliable validation of hygrothermal simulations to come, the conditions in the attic space beneath the roof are also continuously recorded.

2.2 Hygrothermal simulations

The hygrothermal simulations are performed by applying WUFI® [1], which allows the transient calculation of the coupled heat and moisture transport in building components under real climate conditions. The model was developed at the Fraunhofer Institute for Building Physics and has been experimentally validated by comparison with numerous field tests. The assembly used for the simulations is shown in Figure 15. For the mineral wool a moisture retention curve based on the paper by Peuhkuri et al. [2] and adapted to fit the measured results was used. The curve is shown in Figure 16. The other material parameters are taken from the WUFI® database. As outdoor conditions the measured climate from August 2006 to January 2007 in Holzkirchen including solar radiation and long wave counter radiation from the atmosphere is used. As indoor climate serve the recorded temperature and humidity conditions in the attic space beneath the flat roof. The time period for which experimental and calculation results are compared lasts from August 2006 to January 2007.

If a good agreement between measurement and calculation in Holzkirchen can be achieved, the investigation may be broadened by repeating the simulations with climate conditions at other locations. The selected locations are Copenhagen in Denmark representing a Northern European climate and Naples in Southern Italy representing the warm regions of Europe. The meteorological data sets for Copenhagen and Naples are taken from the ASHRAE climate data which were compiled for building energy calculations [3]. A comparison of the relevant climate data (temperature and radiation) at the selected locations with the weather data of 2006 for Holzkirchen is shown in Figure 17. While the climate of Copenhagen appears to be mild compared to Holzkirchen, Naples shows higher air temperatures but not much difference in peak radiation.

The indoor climate is assumed to be the same at all locations. According to the WTA-Guideline 6-2 [4] sinusoidal curves between 20 °C / 40% RH in winter and 22 °C / 60 % RH in summer represent the indoor conditions in residential buildings with normal moisture load. However, since the roof is water and vapour tight the humidity conditions are rather irrelevant.

3 Results

3.1 Field test

The field test described above is still ongoing - for the current report a time period of six months from August 2006 to January 2007 is analyzed. The outdoor climate of the observed time period is plotted in Figure 18. The temperatures during the winter 2006 / 07 were quite moderate with only little snow. There were only a few days with temperatures below -5 °C while in a normal cold winter the temperatures can drop to -20 °C at times. The temperature and relative humidity in the attic space during the observed period is shown in Figure 19. The temperature drop below 10 °C in the first two weeks of November is caused by a failure of the space heating system.

The measured temperature and relative humidity within the construction are shown and discussed in comparison with the calculated results in Figure 20 to Figure 28. In the result diagrams the three sensor positions located at the centre of the roof sections are labelled from outside to inside with "exterior", "middle" and "interior".

3.2 Comparison of calculation and experiment – Validation of transient calculations

In the first step the calculation results for Holzkirchen are compared to the measured temperature and humidity conditions in the two test roof sections with 90 mm and 175 mm of glass fibre insulation.

3.2.1 Flat roof with 90 mm insulation

Figure 20 shows the measured (blue curve, sensor beneath the roofing membrane) and calculated (red curve) surface temperature of the roof with 90 mm insulation layer. The agreement between the two curves is very good - only sometimes the peak values show a small difference of two or three degree Celsius. The comparison with the outdoor air temperature (black curve) shows the strong influence of solar radiation (energy source during day-time) and sky radiation (energy sink during night-time) which is accurately captured by the new model for radiation and surface heat exchange in WUFI® version 4.1.

Figure 21 shows the relative humidity at the three positions within the insulation layer. The overall agreement between measured and calculated curves is quite acceptable. At the exterior position of the insulation the calculated and the measured curves coincide rather well. This is important, since the most extreme temperature and humidity conditions in the insulation layer are observed at the exterior sensor. In summer the RH at this position varies between 20 % at noon (when the sun shines and heats up the exterior surface) and 100 % during night. With lower temperatures and shorter days in autumn and winter the RH at noon increases and remains from midmonth of November permanently at 100 %.

A more detailed plot of the hygrothermal conditions for two single weeks in summer and winter (Figure 22) confirms the generally good agreement between simulation and experiment. The deviation in surface temperature on Dec. 20 is due to a thin snow cover of the roofing membrane which is disregarded in the simulation. An important observation concerning the durability assessment of the glass fibre insulation is the opposed variation of temperature and RH beneath the surface of the roofing membrane in Figure 22. Every time, the temperature rises the relative humidity measured res. calculated for the same position drops in an inverse manner. That means high temperature and high RH never coincide at this point.

At the middle and the interior positions of the insulation layer the mean progression of the curves is very similar, but the spread of the measured values is slightly larger to both directions compared to the calculation. This difference may be due to a remaining uncertainty concerning the material properties (sorption isotherm, vapour diffusion resistance) of the glass fibre boards or the assumption of the initial water content in the roof. In the middle of the insulation the RH varies between about 40 % and 100 % RH from August to November, in December and January the maximum RH reaches about 90 % (measurement) res. 85 % (calculation) and the minimum lies at 60 % RH for both, measurement and calculation.

At the interior position of the insulation the RH is at 100 % from August to November, as the inserted water remains during the somewhat warm outdoor climate on the bottom of the roof. With the colder winter months the water evaporates, moves to the top of the roof and condenses at the cold roofing membrane. Therefore in winter the interior layer of the insulation dries out and remains dry most of the time. Only on sunny days the diffusion transport from the warm roofing membrane leads to peaks up to 100 % RH at the bottom of the insulation (interior position).

3.2.2 Flat roof with 175 mm insulation

The surface temperatures for the roof with 175 mm insulation are shown in Figure 23. Again, the agreement between field test and simulation is very good as already observed by analyzing the roof with 90 mm insulation. This proves that the convective heat transfer coefficient ($h_{c,o}$ = 10 W/m²K) as well as the short wave absorptivity (a_s = 0,66) and the long wave emissivity (ε = 0,9) of the roofing membrane, which are part of the boundary conditions for the simulation, were specified correctly.

The resulting RH in the roof with 175 mm insulation is plotted for the exterior and the middle sensor position in Figure 24. The interior sensor shows a constant RH of 100 % over the whole experimental period. However, the moisture pins in the small wood sample sensors which were installed for crosschecking (Figure 11), show a fast decreasing water content around the beginning of December (Figure 25). Therefore it must be assumed that the capacitive humidity sensor has become defect. This may be caused by being in contact with liquid water for a few months. Since it is unlikely that this sensor can be recovered there will be no reliable experimental data for the humidity at the bottom of the 175 mm thick insulation layer.

While there is a very good match between calculated and measured RH in the middle of the insulation layer, the simulated RH at the exterior sensor position tends to be higher than the measured RH especially during the night. This becomes even more evident in Figure 26. During the selected late summer period the RH of the simulation goes up to 100 % every night when the roof surface temperature drops down to almost 0 °C. The measured RH, however, only reaches about 90 % and remains flat at that point. This sudden halt at 90 % RH after a steep increase seems unrealistic und indicates either a sensor problem (unlikely considering its performance later on) or a local temperature inhomogeneity.

If there were a temperature difference of only 1.5 K between the sensor position and the coldest spot under the membrane during the night when the surface temperature reaches about 5 °C, the sensor would correctly signal 90 % RH while condensation occurs at the coldest spot. That small temperature difference could happen because the sensor position is slightly below the membrane surface or because of the thermal capacity of the sensor itself which is protected by a metal tube. Since the thermal capacity of the glass fibre insulation is rather small, the thermal inertia of the sensor could have an influence on its close vicinity when large temporal variations of the temperature occur.

Despite these measurement uncertainties, the outcome of the comparison is rather promising especially when the results of the roof with 90 mm insulation are also considered. That means, hygrothermal simulations can provide a realistic picture of the transient temperature and humidity fluctuations and their peaks occurring in flat roofs under different climate conditions.

3.3 Evaluation of peak conditions

Laboratory test have shown that the coincidence of high temperature and high humidity has a significant degradation effect on glass fibre insulation. Under dry conditions, a high temperature doesn't do any harm and a high relative humidity is not a great problem as long as the temperature remains low. Therefore, the measured and calculated hygrothermal conditions in the roof are displayed in a special graph where temperature and humidity are plotted against each other for time intervals of one hour. Such a graph is shown in Figure 27 for the three sensor positions in the roof with 90 mm thick insulation.

As expected from the rather well matching temporal variations the agreement between measured and simulated results of coinciding conditions is quite good for all three positions. The highest temperatures with more than above 60 °C (maximum 70 °C) occur at the exterior position beneath the roofing membrane. However, the coinciding RH values remain very low, between 10 % and 30 %. The maximum RH of 100 % is frequently reached at all sensor positions. While the coinciding temperatures stay around 20 °C at the bottom of the roof (interior position) they can reach a maximum of nearly 40 °C in the middle and upper parts of the roof. The limit curve that will not be exceeded at any position in the insulation layer of the investigated roof can be drawn as a straight green line from 40 °C / 100 % RH to 80 °C / 0 % RH (Figure 27)

The same presentation of results for the roof with the thicker (175 mm) insulation layer can be found with the exception of the interior position (sensor failure) in Figure 28. While there is a good match of experiment and simulation at the middle position there is a distinct shift of the calculated results towards a higher relative humidity at the top position. This phenomena has already been observed and discussed before (Figure 26). It is reasonable to assume that the simulated results which show more severe conditions are closer to reality.

When comparing the coinciding temperature and humidity conditions and their distance from the above mentioned limit curve of both roofs, the hygrothermal conditions appear to be a little more severe in the roof with only 90 mm of insulation. This situation might seem surprising at first sight because more insulation is associated with a higher maximum surface temperature. However, since the surface temperature is almost entirely determined by solar irradiance and surface heat transfer to the exterior there is almost no difference between 90 mm and 175 mm of insulation. But the temperature gradients and hence also the vapour pressure gradients which drive the moisture up and down are greater when the insulation thickness is smaller. It is therefore not uncommon to find slightly more severe hygrothermal conditions in a roof with less insulation. In this investigation the differences in the peak loads of both roofs are, however, very small. Therefore the following calculations for other locations are carried out considering both insulation thicknesses. The selected locations for the hygrothermal simulations are Copenhagen and Naples.

The outdoor air temperature in Copenhagen varies between ca. -10 °C in Winter and 20 °C in summer. The hygrothermal conditions in the insulation layer at the tree monitor positions are shown in Figure 29. The temperature on the exterior monitor shows values between -15 °C and 65 °C. The temporal variations of the relative humidity at the different positions resemble the results obtained for Holzkirchen (Figure 21). The plot of the hourly RH plotted over temperature is displayed in Figure 30. Again, the results are very similar to the data of the flat roof in Holzkirchen (compare with Figure 27). However, the Copenhagen results for the exterior position come a bit closer to the limit curve (green line) and go even slightly over the limit a couple of times.

In order to obtain more detailed information the coincident temperatures and relative humidities are classified in steps of 10 % RH starting with 50 % and steps of 10 K between -10 and +80 °C to analyse the different peak levels. The accumulated results are displayed in a two-dimensional bar diagram in Figure 31 and also listed in Table 1. About 7700 hours a year a RH between 90 % and 100 % prevails, more than 3200 hours thereof at a temperature range between 0 and 10 °C and 1600 between -10 and 0 °C. In the higher temperature ranges the hours where RH exceeds 90 % become increasingly scarce. At Copenhagen the temperature within the construction never exceeds 70 °C. A temperature above 40 °C and a coincident relative humidity of above 80 % occurs during about 90 hours a year - this represents only 1.0 % of the service life of a roof.

Figure 32 shows the hygrothermal conditions at the three positions in the insulation of the flat roof with 175 mm insulation. The temperature at the exterior position shows a very similar behaviour as for the roof with 90 mm in Figure 29.

At the other two monitors the temperature variations are smaller while the average relative humidity remains higher due to the thicker insulation layer. Compared to the roof with only 90 mm insulation Figure 33 ,where the relative humidity is plotted over temperature, shows similar conditions at the exterior and interior position but less severe conditions in the middle of the insulation layer. The classification of coinciding conditions in Figure 34 differs only marginally from the one in Figure 31. The values in Table 2 for the exterior monitor position show again that the RH is close to 100 % most of the time. Temperatures above 40 °C at a relative humidity over 80 % occur for only 100 hours a year (slightly higher compared with Table 1) or during 1.2 % of the service life.

The same hygrothermal analysis is repeated with the climate data for Naples. First the roof with 90 mm of glass fibre insulation is considered which is probably more common for a southern region than a roof with 175 mm insulation. The hygrothermal conditions in the insulation layer at the three monitor positions are shown in Figure 35. At the exterior part of the insulation the temperature now reaches almost 80 °C in summer and falls to about -10 °C in winter. The relative humidity over temperature plot is displayed in Figure 36. Compared to Copenhagen the values show a similar distribution - only the maximum temperature level in summer is 15 K higher but with a lower humidity of just about 10 % RH. The hourly classification of temperature and RH in Figure 37 (values in Table 3) shows with about 6600 fewer hours between 90 and 100 % RH than the locations further north. Due to the higher surface temperature in summer the RH decreases faster during day. Most frequent in Naples are with about 2700 hours conditions from 90 to 100 % RH combined with a temperature between 10 and 20 °C followed by 2200 hours with the same RH at temperatures between 0 and 10 °C. Values above 80 % RH and 40 °C occur during less than 100 hours - so apart from the higher temperatures of 80 °C the number of hours in a higher range of RH and temperature differs hardly from the situation in Copenhagen.

The temperature and humidity plots of the flat roof containing an 175 mm insulation layer are shown in Figure 38. As expected the temperatures are very similar to those in the thinner roof with a smaller variation at the middle and the interior part of the insulation. The distribution of the coincident temperature and RH in Figure 39 shows also a similar shape as in the roof with 90 mm of insulation - only the RH values at high temperatures are slightly higher. The hourly classification of the simultaneous RH and temperature in Figure 40 differs hardly from bar diagram in Figure 37 for the roof with 90 mm insulation. The values in Table 4 show, that the number of hours with 90 to 100 % RH decreases from 6600 to about 6400 while conditions above 80 % RH and 40 ° occur just 91 hours a year, a little less than in the roof with 90 mm insulation.

4 Conclusion

The standards quoted at the beginning of this report specify test conditions for mineral fibre materials with temperatures above 60 °C and RH values between 95 and 100 % during five or seven days which means 120 to 170 hours. The aim of the present study is to find out whether these test conditions really occur in practice under European climate conditions. If that is not the case more realistic test conditions should be determined.

The measured conditions in the flat roof in Holzkirchen as well as the simulation results for locations in northern and southern Europe show, that a RH above 95 % in combination with a temperature of more then 60 °C will never occur in a vapour permeable insulation material like mineral fibre - even if there is a high initial water content in the roof of about 2 kg/m². The results indicate an opposed correlation between temperature and relative humidity: a high vapour pressure resulting from a rising temperature immediately causes a strong diffusion transport into areas with lower vapour pressure res. temperature.

Therefore the potentially damaging condition of coinciding peaks in temperature and RH never occurs. The investigation proved that the simultaneous occurrence of humidity conditions above 80 % RH and maximum temperatures between 40 and 50 °C at the most critical position within the insulation layer of a flat roof (beneath the roofing membrane) does generally not exceed 100 hours a year under European climate conditions.

It should be noted that these conditions do not prevail continuously for several subsequent hours and they do not affect the entire insulation layer. They represent only short peaks that happen under particular weather situations at the most exposed part of the insulation layer, the zone directly below the roofing membrane. Other parts of the glass fibre boards experience less severe conditions.

A material test procedure for durability assessments should accelerate the normal degradation process but not make fail a material which performs well in reality. Therefore, it is recommended to specify the durability test conditions as close as possible to the conditions in real life while still remaining somewhat on the safe side. It is therefore proposed to define those conditions based on the study presented here. Both the experimental results and the simulations have shown that coinciding peaks of temperature und relative humidity ranging from 40 °C to maximum 50 °C res. from 80 % to 100 % (average 90 % RH) add up to less than 100 hours per year. Consequently, there is good reason to set the durability test conditions to 50 °C and 90 % RH.

However, the question concerning the duration of such test remains. Field tests periodically checking the durability of mineral fibre insulation in external wall insulation systems have shown that the greatest loss in pull-off strength happens in the first few month of service life. After that period the mechanical properties remain stable [5]. Continuous exposure of mineral wool to constant test conditions in the laboratory may show a slightly different picture (e.g. [6]), but they do not reflect the permanently altering hygrothermal conditions in the real world. The field tests indicate that there are periods (probably those with dominantly dry conditions) where the insulation material seem to recover its strength. This cannot happen during prolonged laboratory tests with constant peak conditions lasting 1000 hours or more. Thus, a test period in excess of the summed-up intervals of peak conditions occurring during a year in a real flat roof do not make much sense. It is therefore proposed to limit the test period to one week which is still on the safe side compared to the 100 hours of peak conditions actually occurring.

For this conclusion, the long-term performance of glass fibre boards in flat roof constructions is assumed to be comparable to that of mineral fibre boards in external thermal insulation composite systems (ETICS), where the temporal development of the pull-off strength has been determined by field tests. In order to confirm this assumption field tests monitoring the compressive strength of glass fibre insulation in flat roofs should be carried out in future.

5 Literature

[1] Künzel, H.M.: Simultaneous Heat and Moisture Transport in Building Components. One- and two-dimensional calculation using simple parameters. IRB-Verlag Stuttgart 2005.

[2] Peuhkuri, R., Rode, C. and Hansen, K.K. (2005): Effect of method, step size and drying temperature on sorption isotherms. 7th Nordic Symposium on Building Physics, Reykjavík, pp. 31-38.

[3] ASHRAE: International Weather for Energy Calculations (IWEC) CD-ROM, Atlanta 2001.

[4] WTA-Guideline 6-2-01/ E: Simulation of heat and moisture transfer. Fraunhofer IRB Verlag, 2004, ISBN 978-3-8167-6827-2

[5] Zirkelbach, D., Holm, A. & Künzel, H.M.: Influence of temperature and relative humidity on the durability of mineral wool in ETICS. Proceedings 10DBMC, Lyon April 2005, TT2-87.

[6] Franke,L. & Deckelmann, G.: Vergleich der Auswirkungen hygrothermischer Beanspruchungen von Mineralfaserdämmstoffen im baupraktischen Einsatz und unter Laborbedingungen. Proceedings 10th International Symposium for Building Physics, Dresden 1999, pp 587-596.

6 Tables

Table 1: Hourly classification of the simultaneous RH and temperature at the exterior position of the flat roof with 90 mm of glass fibre insulation for Copenhagen.

		Relative humidity [%]					
		0 - 50%	50 - 60%	60 - 70%	70 - 80%	80 - 90%	90 - 100%
Temperature [°C]	< -10°C						189
	-10 - 0°C						1634
	0 - 10°C						3262
	10 - 20°C					1	1618
	20 - 30°C			8	47	86	640
	30 - 40°C	16	48	86	61	74	305
	40 - 50°C	143	67	52	52	35	49
	50 - 60°C	197	14	7	6	3	2
	60 - 70°C	56					
	70 - 80°C						
	>80°C						

Table 2: Hourly distribution of the simultaneous RH and temperature at the exterior monitor of the roof with 175 mm of insulation in Copenhagen.

		Relative humidity [%]					
		0 - 50%	50 - 60%	60 - 70%	70 - 80%	80 - 90%	90 - 100%
Temperature [°C]	< -10°C						197
	-10 - 0°C						1762
	0 - 10°C						3221
	10 - 20°C					11	1532
	20 - 30°C			2	35	89	635
	30 - 40°C	4	32	83	111	97	247
	40 - 50°C	89	96	78	44	29	60
	50 - 60°C	166	28	24	15	11	1
	60 - 70°C	59					
	70 - 80°C						
	>80°C						

Table 3: Hourly distribution of the simultaneous RH and temperature at the exterior monitor of the roof with 90 mm of insulation in Naples.

		Relative humidity [%]					
Temperature [°C]		0 - 50%	50 - 60%	60 - 70%	70 - 80%	80 - 90%	90 - 100%
	< -10°C						11
	-10 - 0°C						599
	0 - 10°C						2177
	10 - 20°C					26	2659
	20 - 30°C			37	56	166	778
	30 - 40°C	41	108	53	67	110	348
	40 - 50°C	240	80	83	41	49	48
	50 - 60°C	384	26	10	4		
	60 - 70°C	409					
	70 - 80°C	148					
	>80°C						

Table 4: Hourly distribution of the simultaneous RH and temperature at the exterior monitor of the roof with 175 mm of insulation in Naples.

		Relative humidity [%]					
Temperature [°C]		0 - 50%	50 - 60%	60 - 70%	70 - 80%	80 - 90%	90 - 100%
	< -10°C						7
	-10 - 0°C						634
	0 - 10°C						2196
	10 - 20°C					180	2451
	20 - 30°C		2	31	100	144	754
	30 - 40°C	29	98	87	99	83	319
	40 - 50°C	235	93	64	58	54	36
	50 - 60°C	366	39	18	3	1	
	60 - 70°C	414	1				
	70 - 80°C	161					
	>80°C						

7 Figures

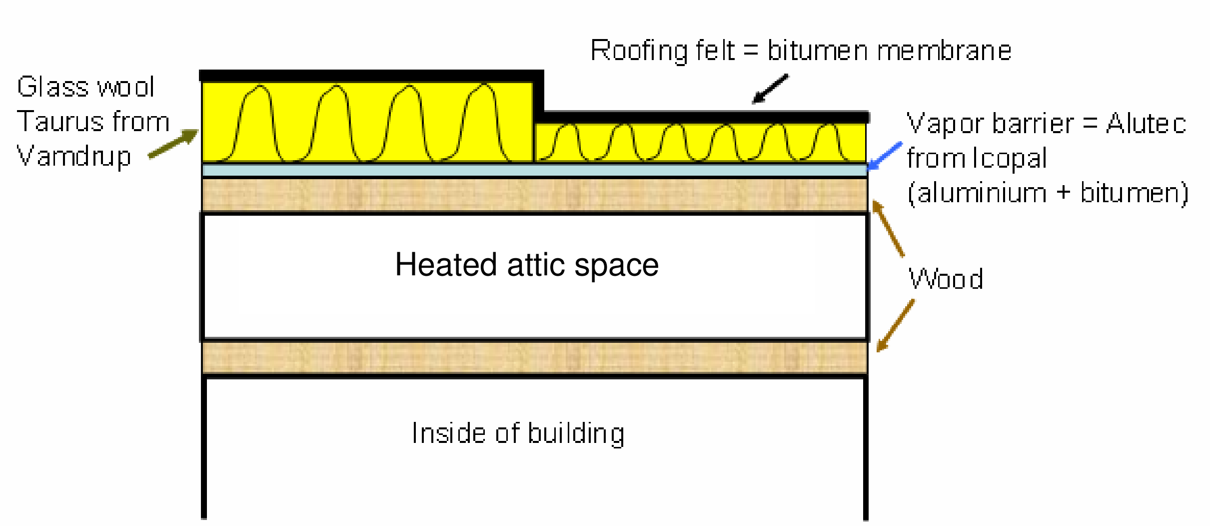

Figure 1: Schematic drawing of the investigated flat roof sections with 90 mm and 175 mm of glass fibre insulation.

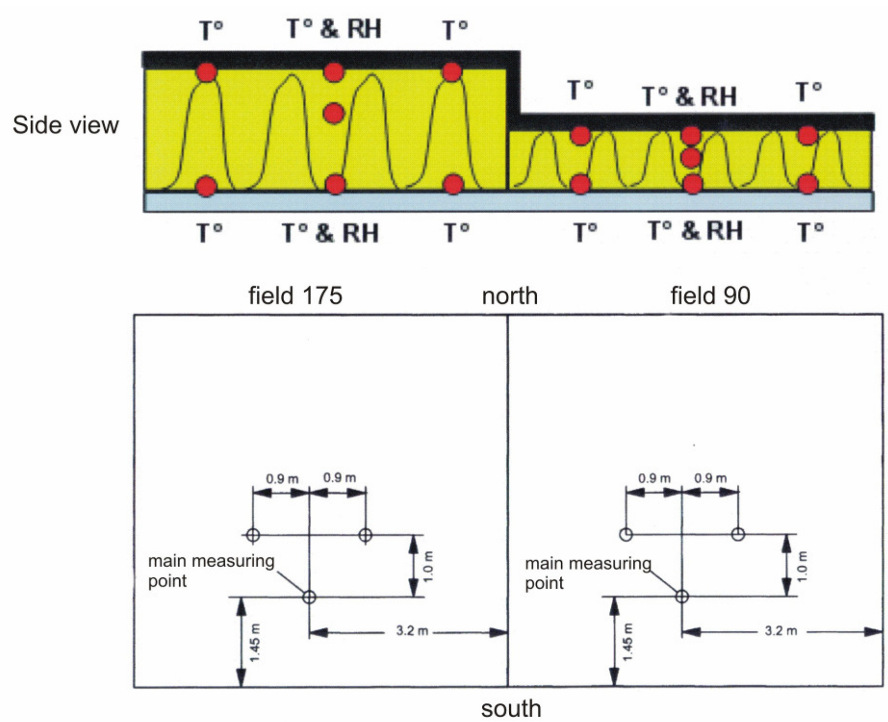

Figure 2: Sensor positions in the test roof. The data recorded at the centre positions are used for validating the hygrothermal simulations.

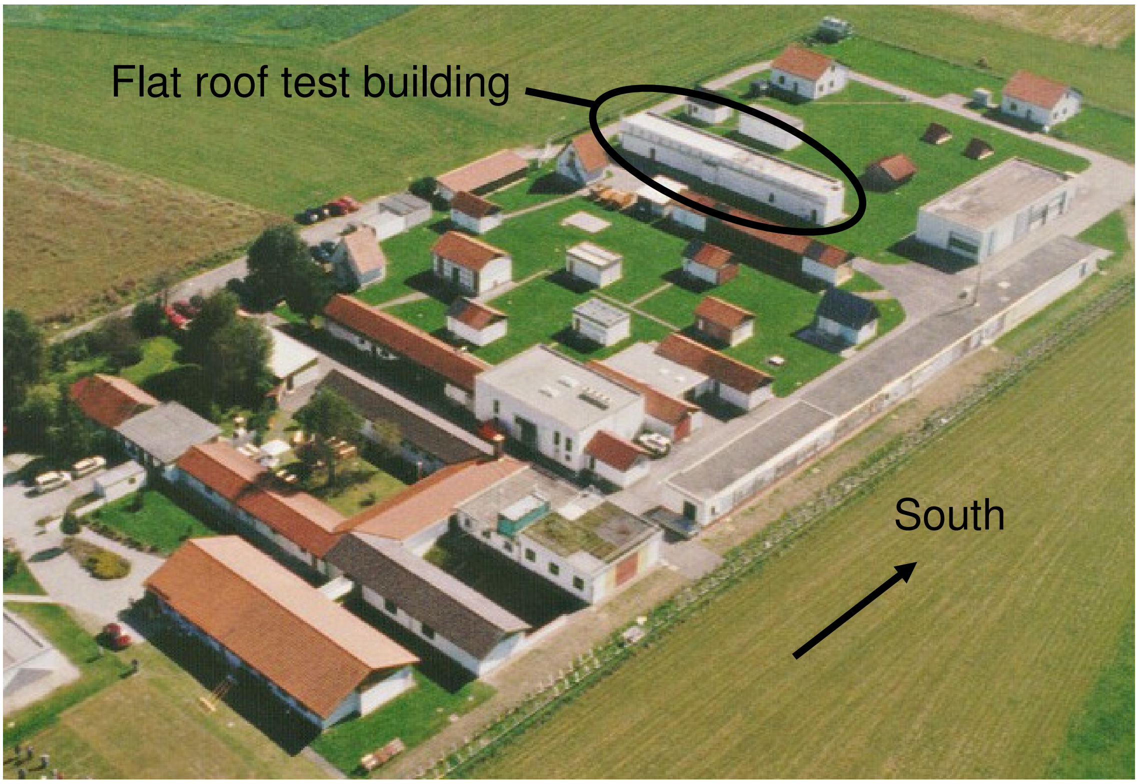

Figure 3: Location of the flat roof test building at the IBP field test site in Holzkirchen.

Figure 4: Installation of electrical wire heating and preparation of the load bearing roof structure above the attic space.

Figure 5: Airtight application of the aluminium vapour barrier on the wooden sheathing over the attic space.

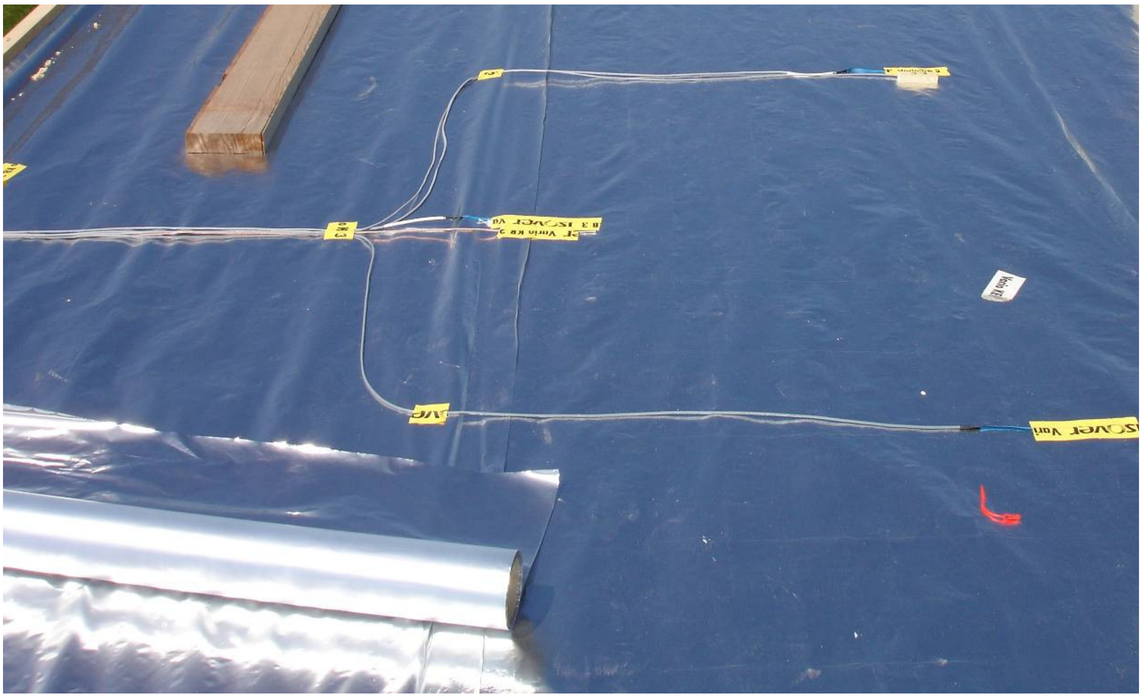

Figure 6: Installation of the interior sensors (below the glass fibre boards) for RH and temperature measurement. In the middle, a PT100 is combined with a capacitive RH sensor. Additional PT100 sensors, one combined with a wood moisture sensor, can be seen at the top and bottom of the photograph.

Figure 7: Laying of the wet insulation boards on the vapour barrier.

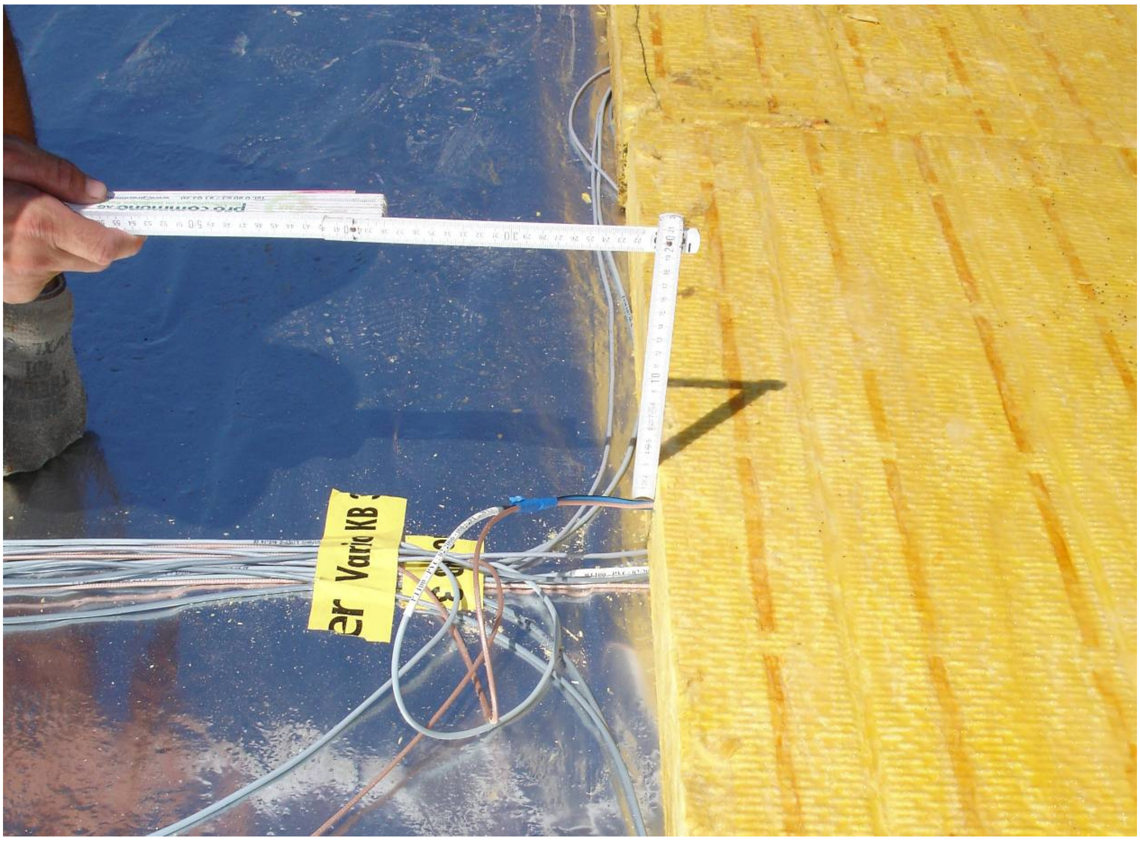

Figure 8: Installation of temperature and humidity sensors within the insulation layer at an eccentric middle position (one third from the top).

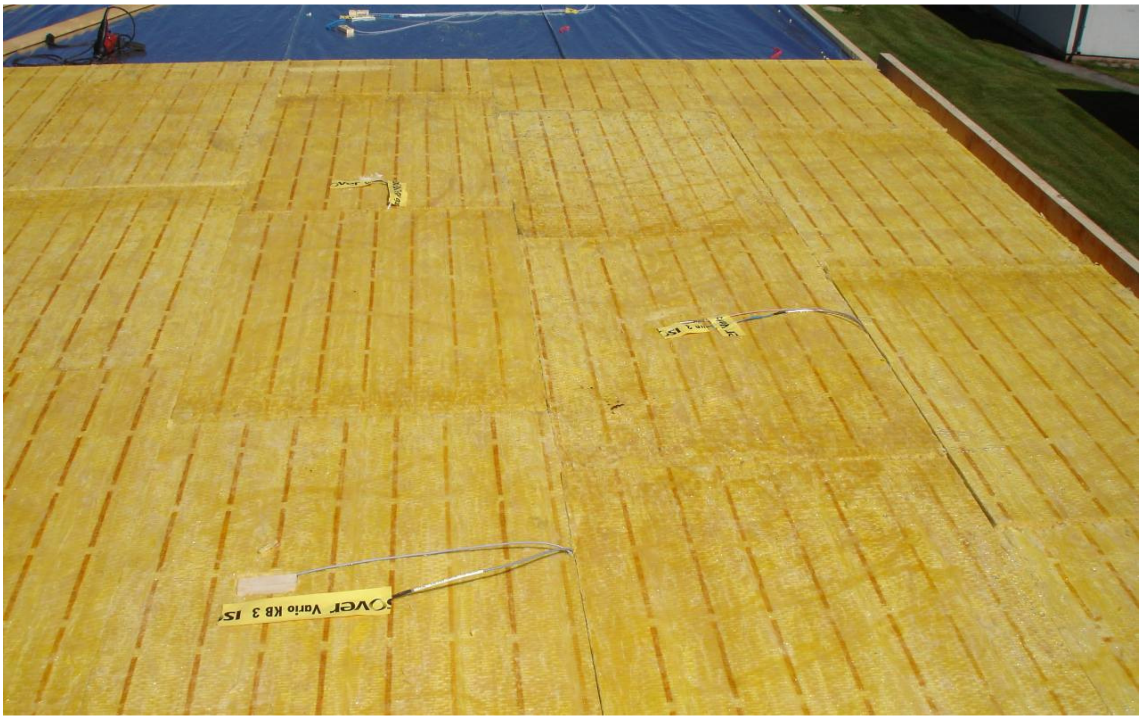

Figure 9: Installation of the exterior sensors (on top of the insulation layer) for RH and temperature measurement.

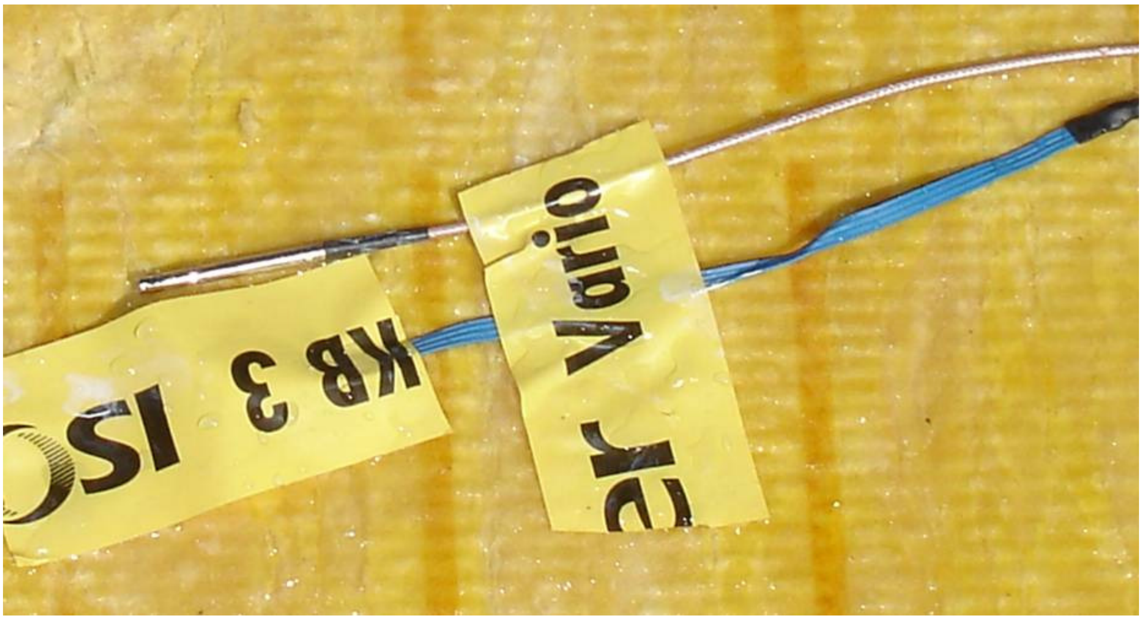

Figure 10: Close look at the capacitive humidity sensor protected by a metal tube installed next to the PT100 (blue wire) on top of the insulation layer.

Figure 11: Close look at the wooden cubes with electrical resistance moisture sensors next to a PT100 on top of the insulation layer.

Figure 12: Spray-wetting of the glass fibre boards before installation.

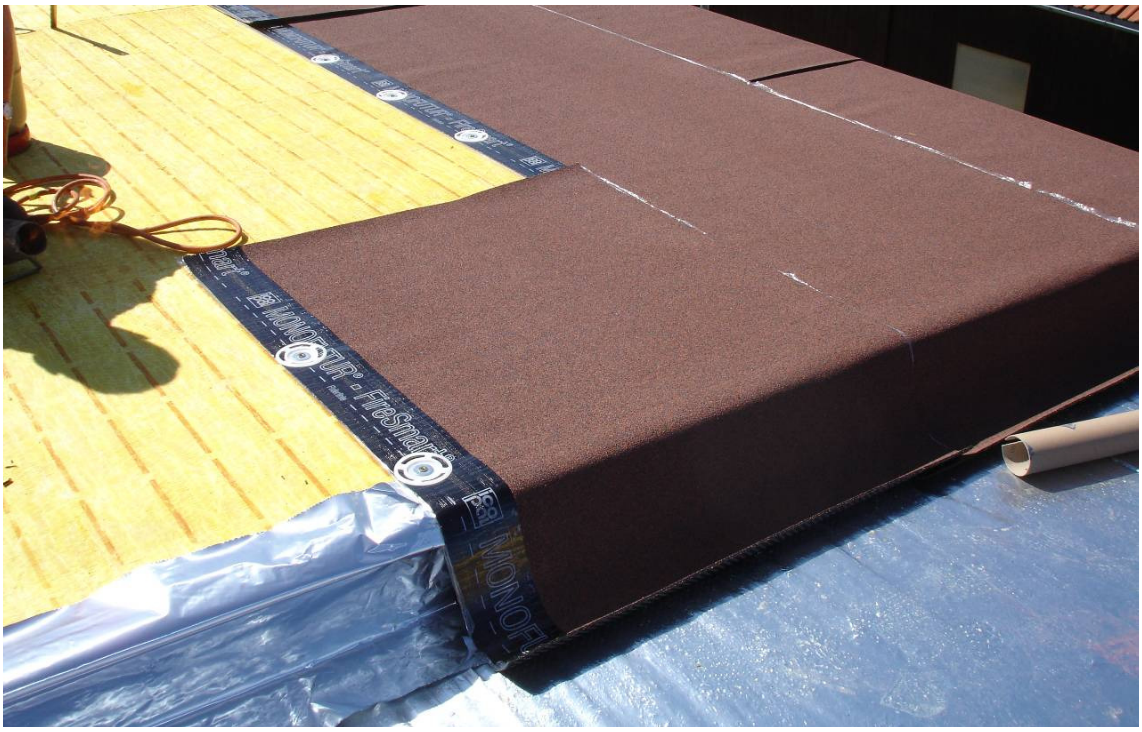

Figure 13: Sealing of the roof section by applying the roofing membrane.

Figure 14: View of the finished flat roof sections from the top and from the south side of the test building.

:

Figure 15: Composition of the flat roof construction with the numerical grid for hygrothermal simulation. The impermeable roofing membrane at the left hand side is accounted for by an appropriate diffusion resistance.

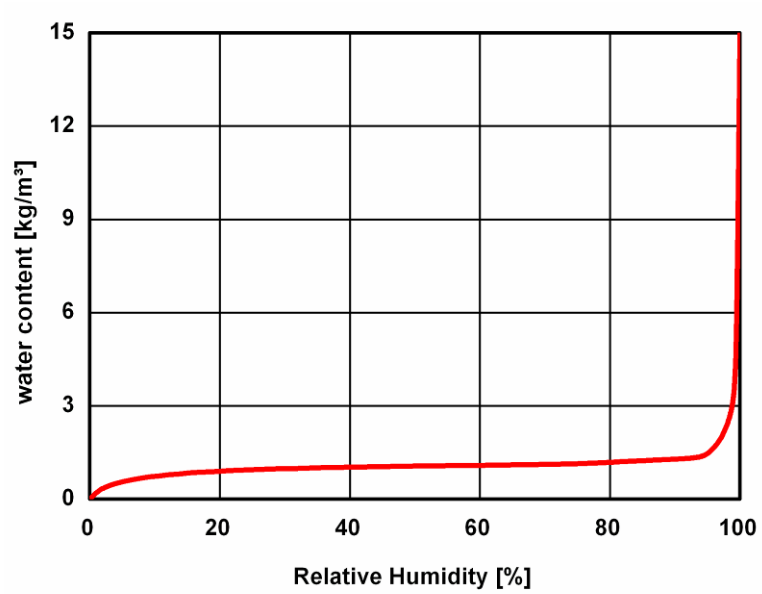

Figure 16: Moisture retention curve of glass fibre insulation employed for the hygrothermal simulation.

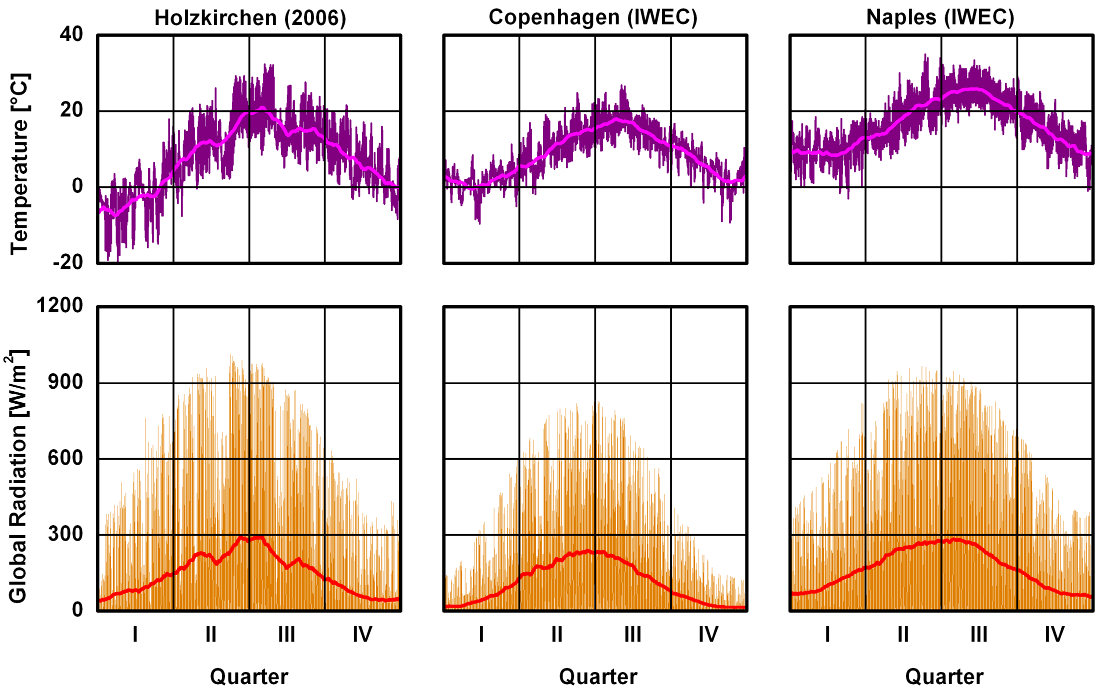

Figure 17: Outdoor air temperature (top) and solar radiation (bottom) of Holzkirchen, Copenhagen and Naples displayed as hourly fluctuation and running monthly average.

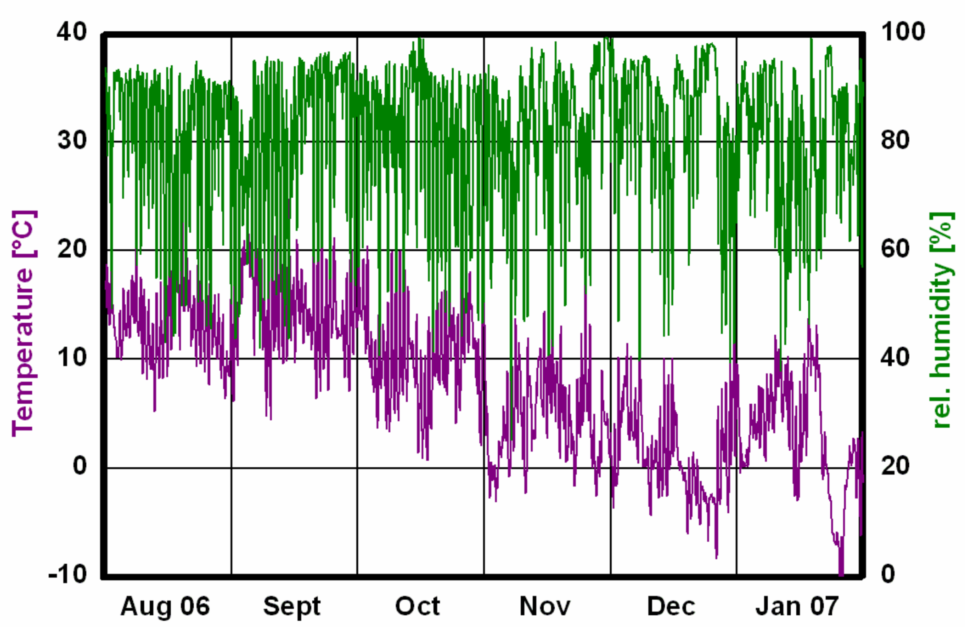

Figure 18: Outdoor climate in Holzkirchen during the investigation period.

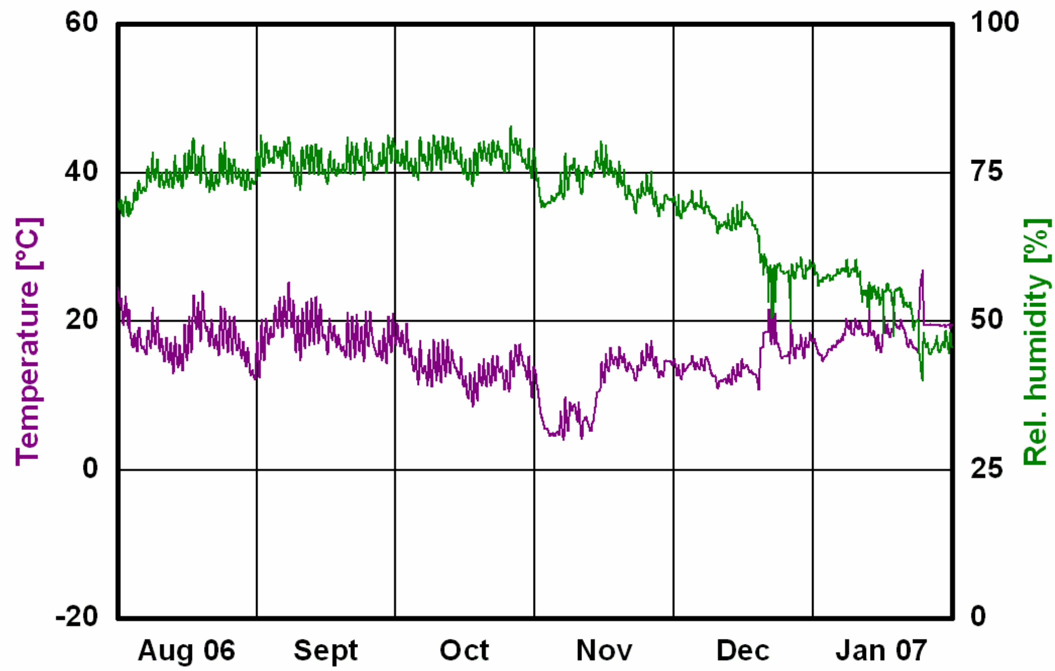

Figure 19: Indoor climate in the attic space during the investigation period.

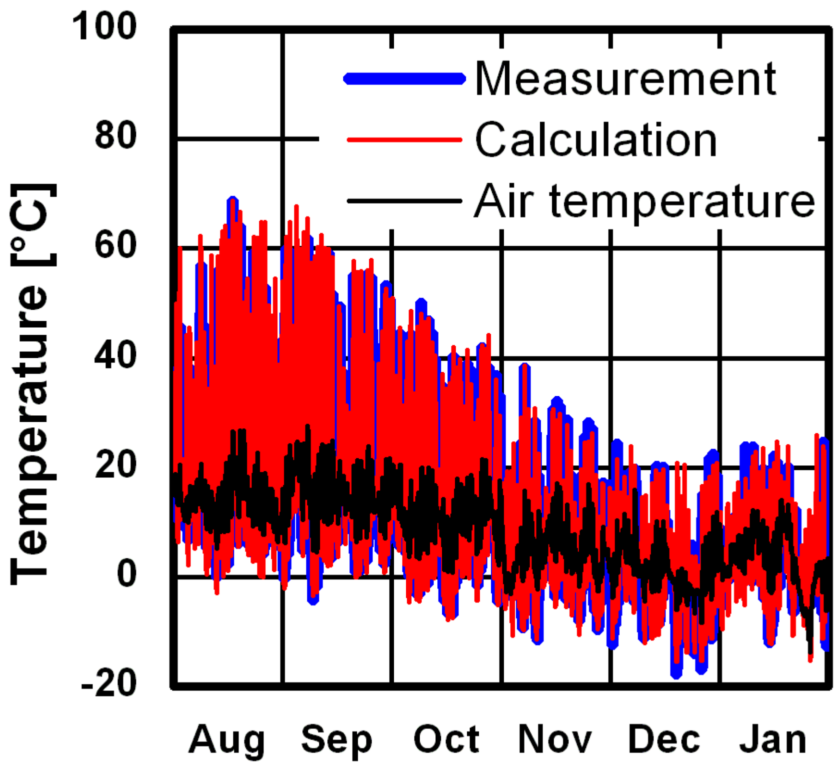

Figure 20: Comparison of measured and calculated exterior temperature variations (position beneath the roofing membrane) in the roof with 90 mm insulation under the indoor and outdoor climate conditions recorded during the test in Holzkirchen.

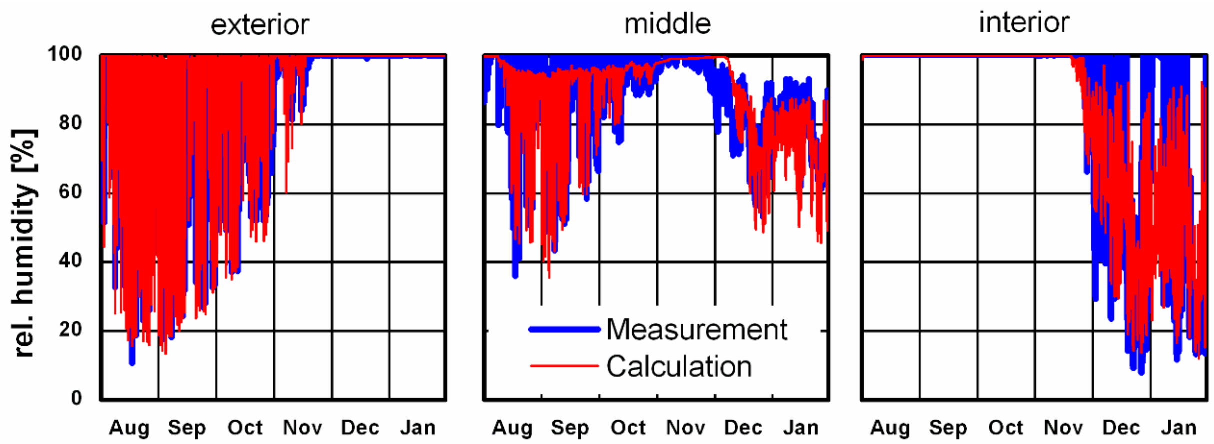

Figure 21: Comparison of measured and calculated relative humidity variations at the three sensor position in the roof with 90 mm insulation under the indoor and outdoor climate conditions recorded during the test in Holzkirchen.

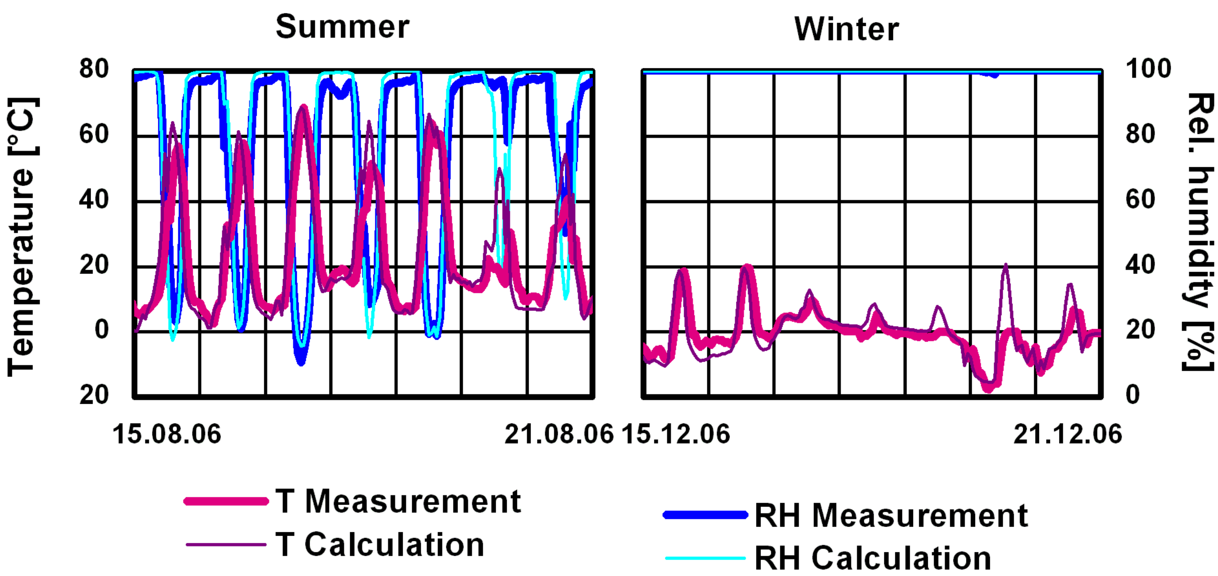

Figure 22: Comparison of measured and calculated temperature and humidity variations at the exterior sensor position in the roof with 90 mm insulation for two selected weeks in August and December.

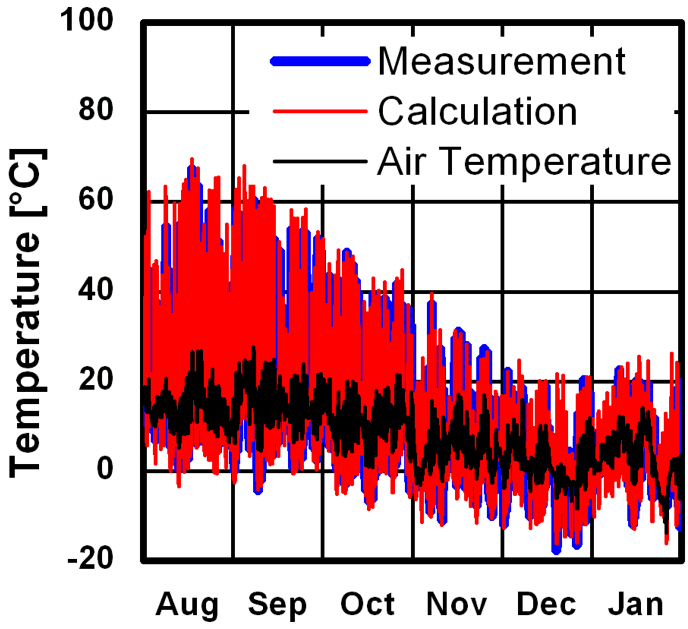

Figure 23: Comparison of measured and calculated exterior temperature variations (position beneath the roofing membrane) in the roof with 175 mm insulation under the indoor and outdoor climate conditions recorded during the test in Holzkirchen.

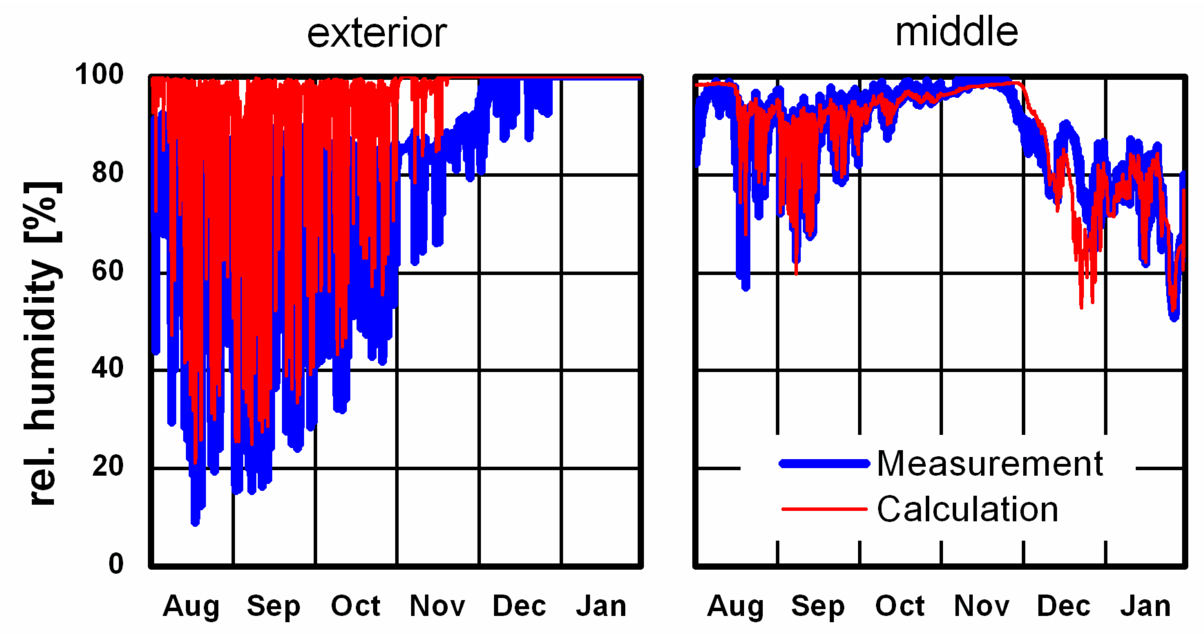

Figure 24: Comparison of measured and calculated relative humidity variations at the exterior sensor position and in the "middle" (60 mm beneath roofing membrane) of the roof with 175 mm insulation under the indoor and outdoor climate conditions recorded during the test in Holzkirchen.

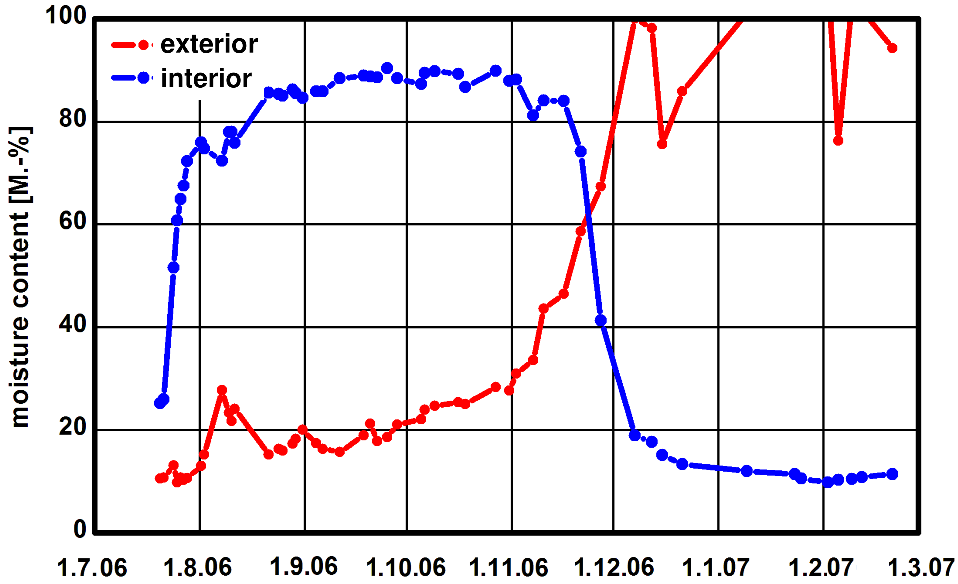

Figure 25: Temporal variation of the moisture content of small wood samples at the top and bottom of the 175 mm thick glass fibre boards measured with moisture pins about twice a week.

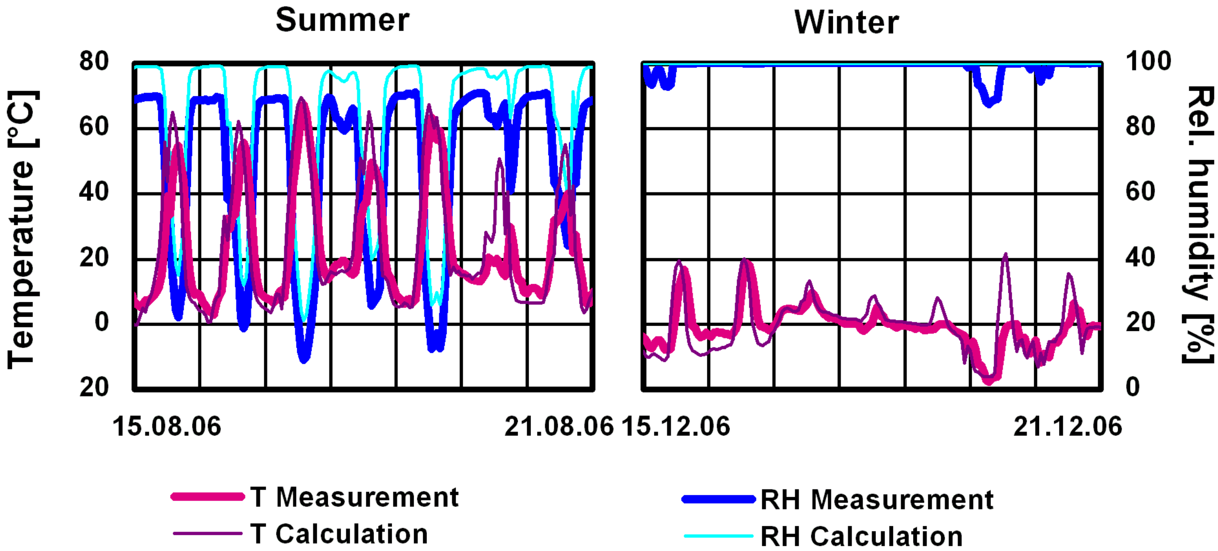

Figure 26: Comparison of measured and calculated temperature and humidity variations at the exterior sensor position in the roof with 175 mm insulation for two selected weeks in August and December.

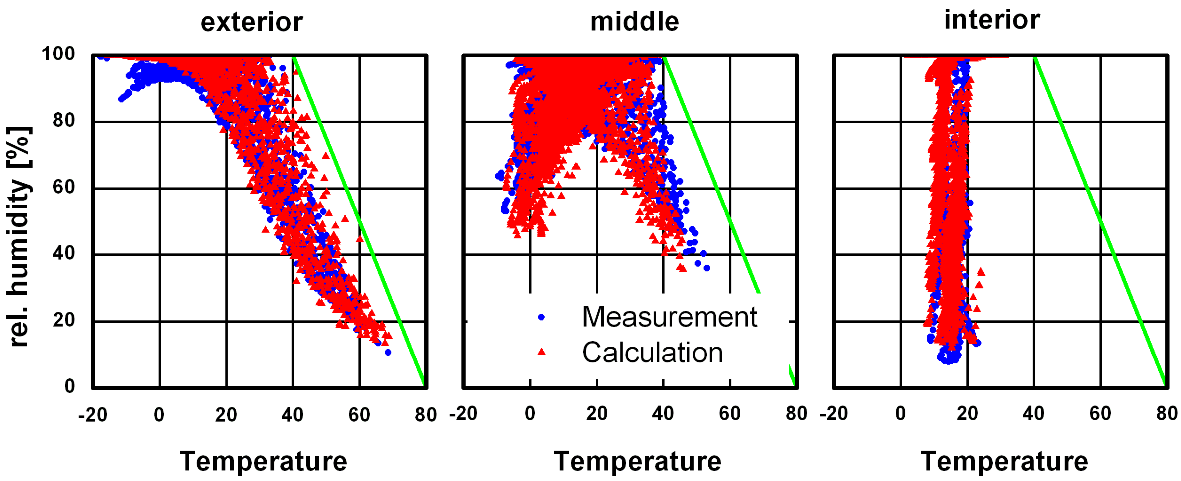

Figure 27: Coinciding temperature and humidity conditions on an hourly basis measured and calculated at three sensor positions in the roof with 90 mm insulation. The green line represents the limiting curve for the hygrothermal conditions determined for the climate conditions in Holzkirchen.

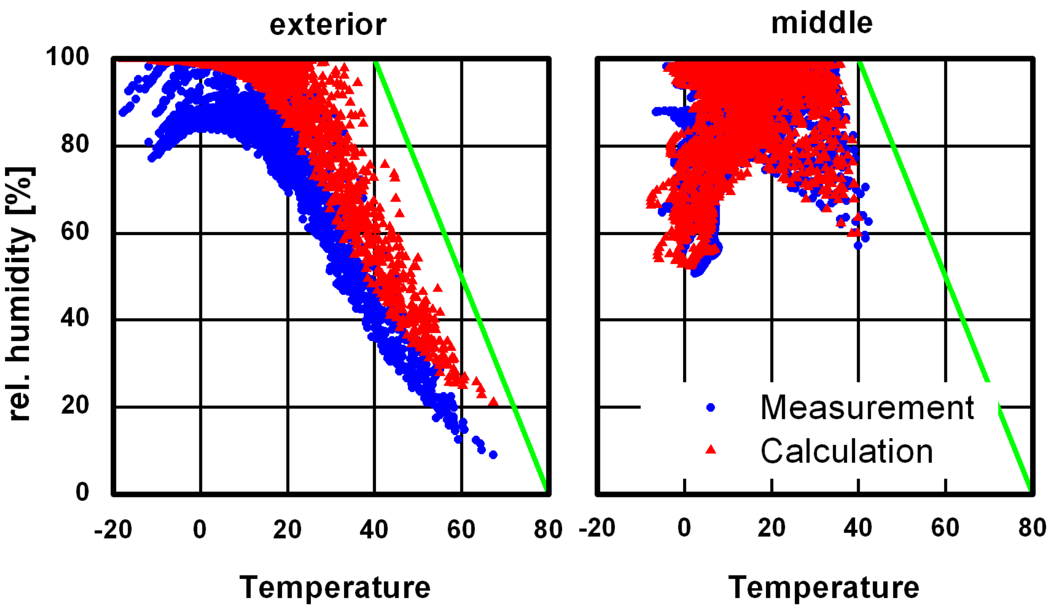

Figure 28: Coinciding temperature and humidity conditions on an hourly basis measured and calculated at two sensor positions in the roof with 175 mm insulation in Holzkirchen.

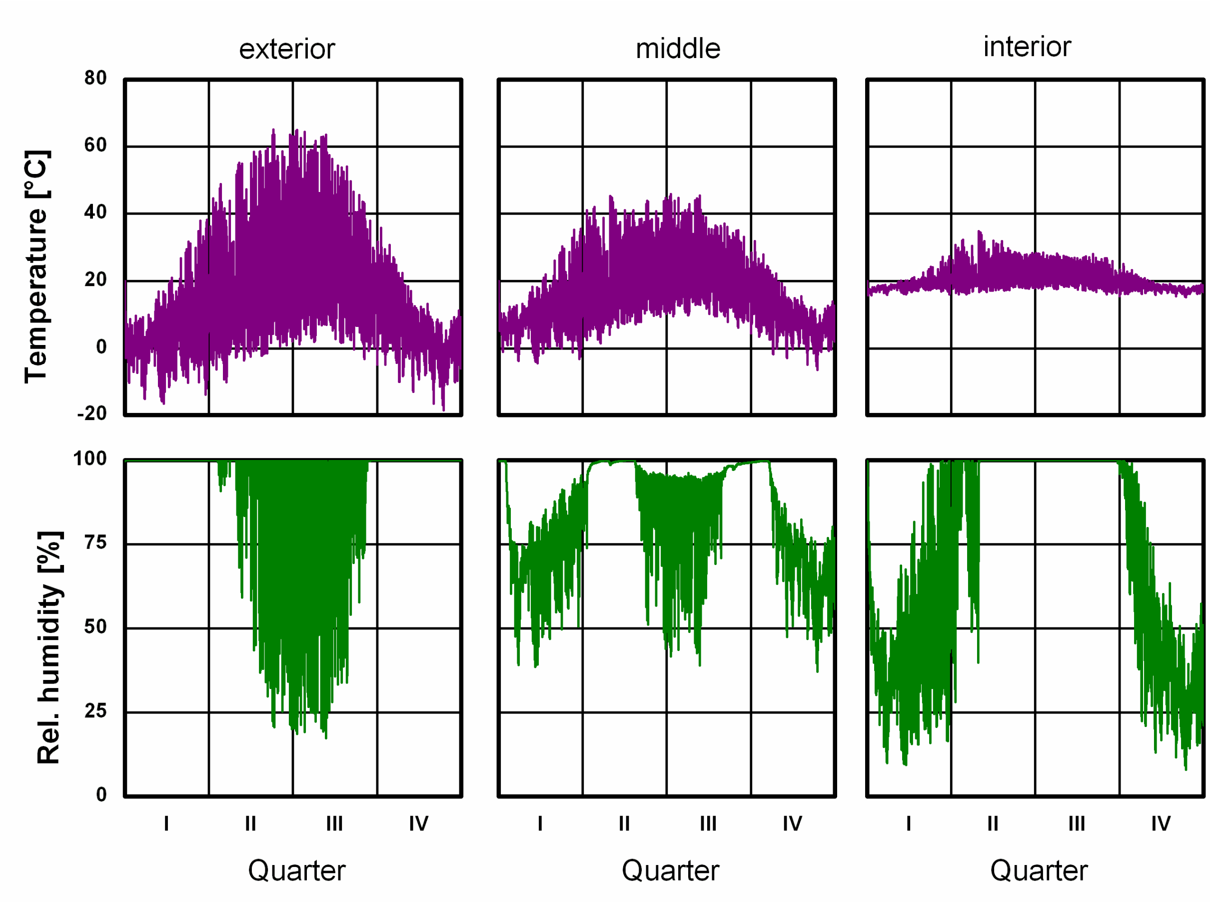

Figure 29: Calculated temperature and humidity conditions at different positions within a flat roof with 90 mm glass fibre insulation in Copenhagen.

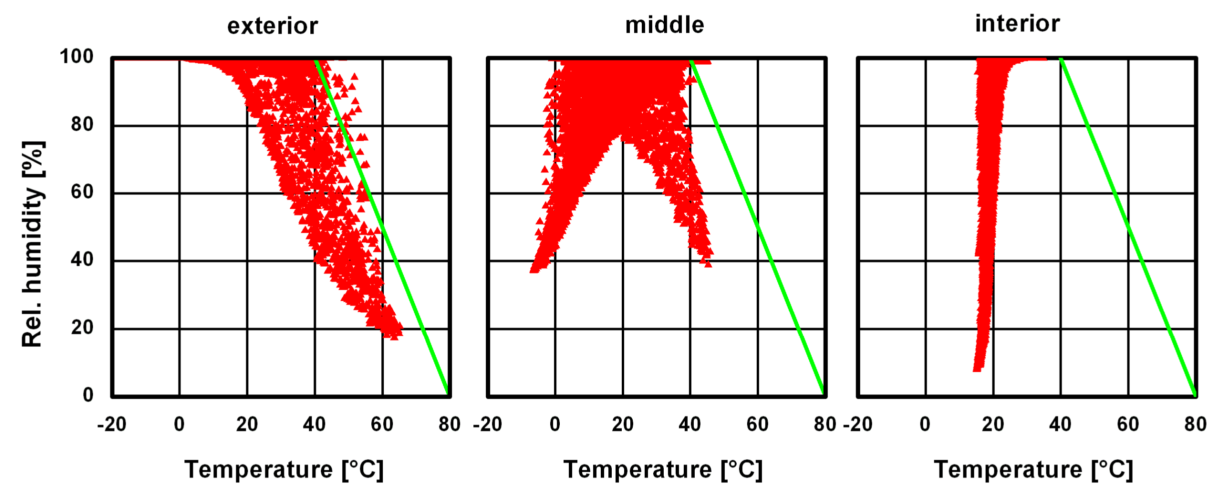

Figure 30: Coinciding temperature and humidity conditions on an hourly basis calculated at three monitor positions within the roof with 90 mm insulation located in Copenhagen. The green line represents the limiting curve first defined in Figure 27.

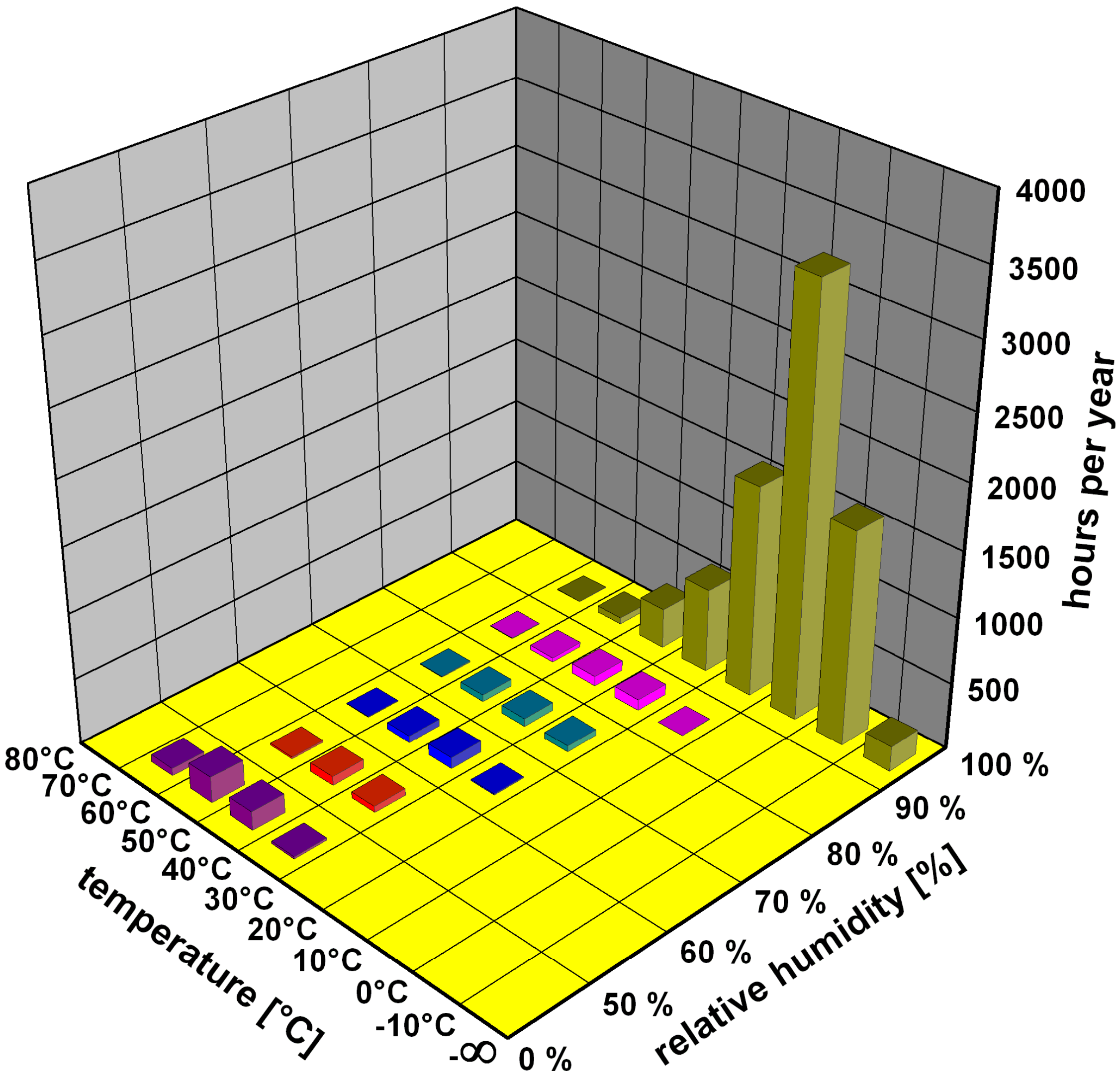

Figure 31: Classification of the coinciding temperature and humidity conditions at the exterior surface of the 90 mm glass fibre insulation (where the most severe hygrothermal conditions occur) for the climate in Copenhagen.

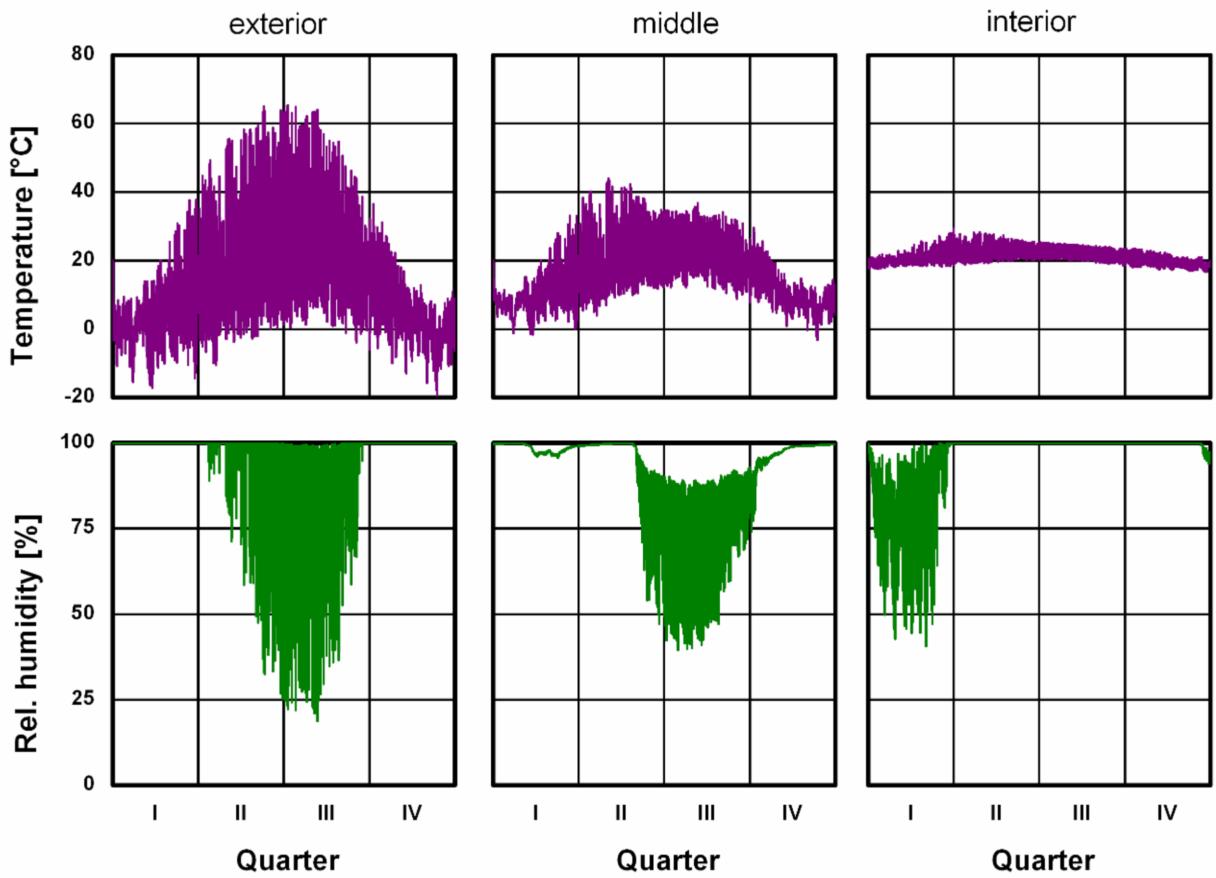

Figure 32: Calculated temperature and humidity conditions at different positions within a flat roof with 175 mm glass fibre insulation in Copenhagen.

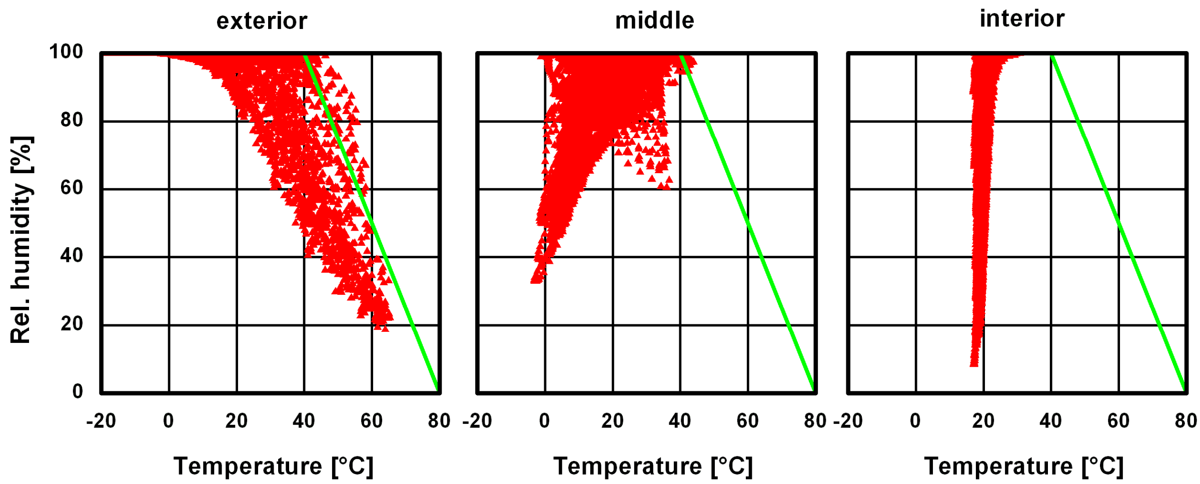

Figure 33: Coinciding temperature and humidity conditions on an hourly basis calculated at three monitor positions within the roof with 175 mm insulation located in Copenhagen. The green line represents the limiting curve first defined in Figure 27.

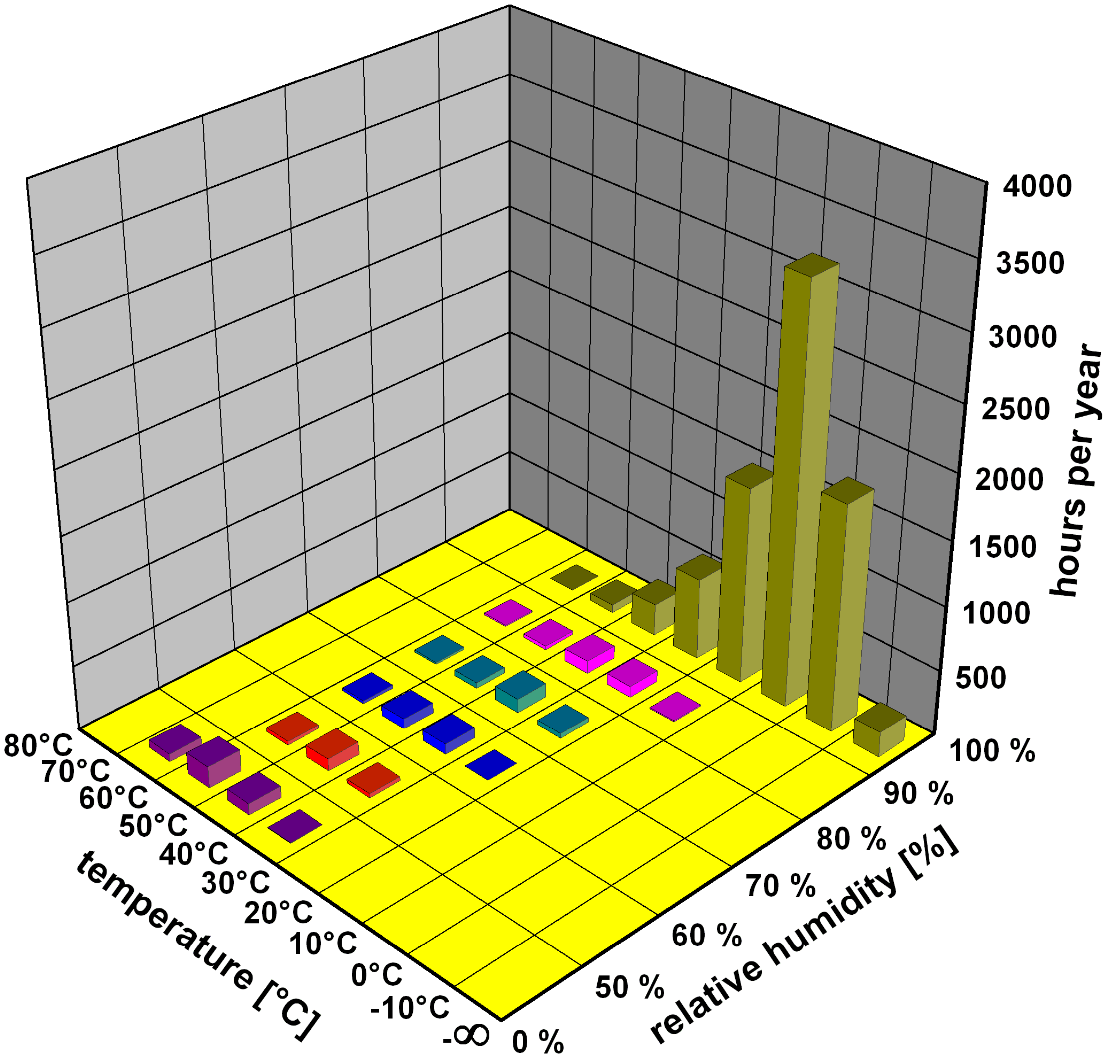

Figure 34: Classification of the coinciding temperature and humidity conditions at the exterior surface of the 175 mm glass fibre insulation for the climate in Copenhagen.

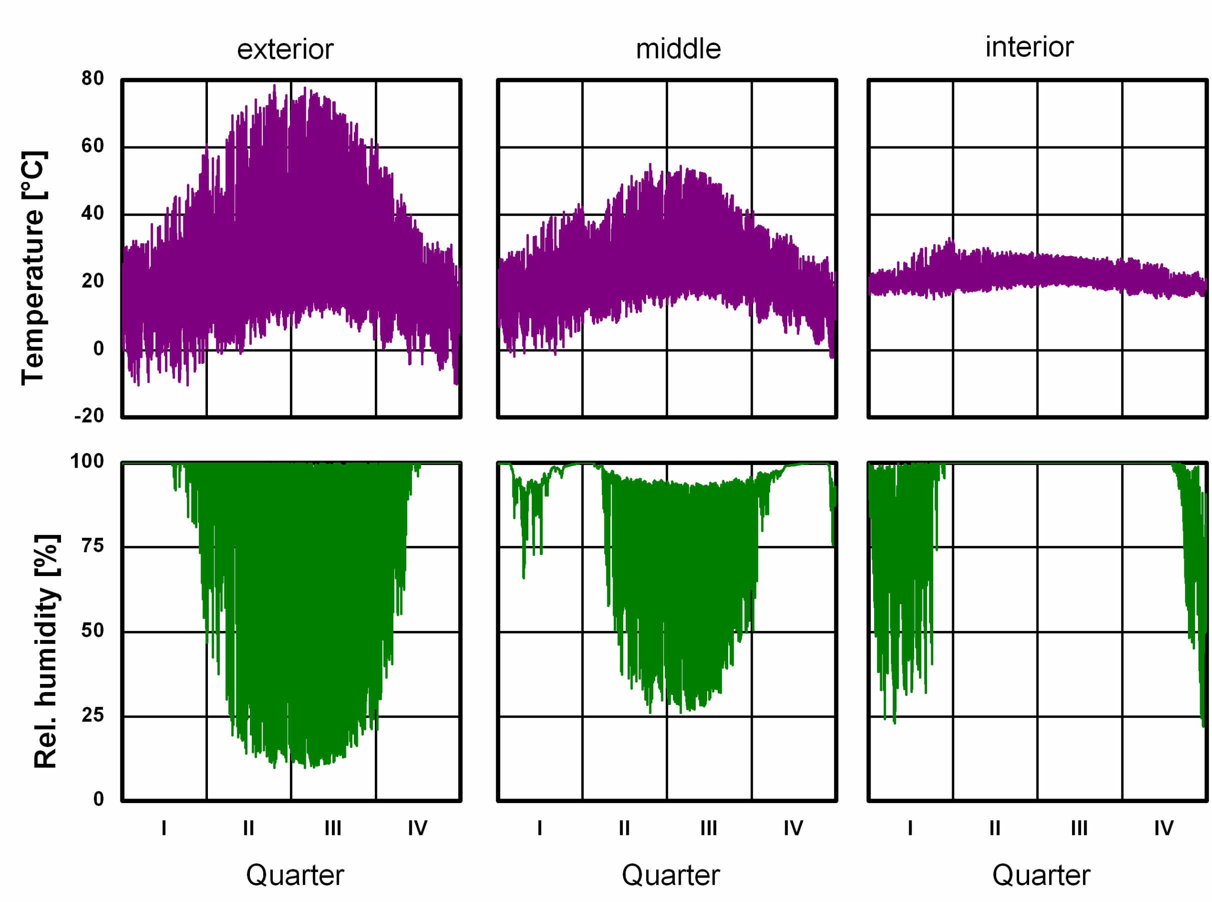

Figure 35: Calculated temperature and humidity conditions at different positions within a flat roof with 90 mm glass fibre insulation in Naples.

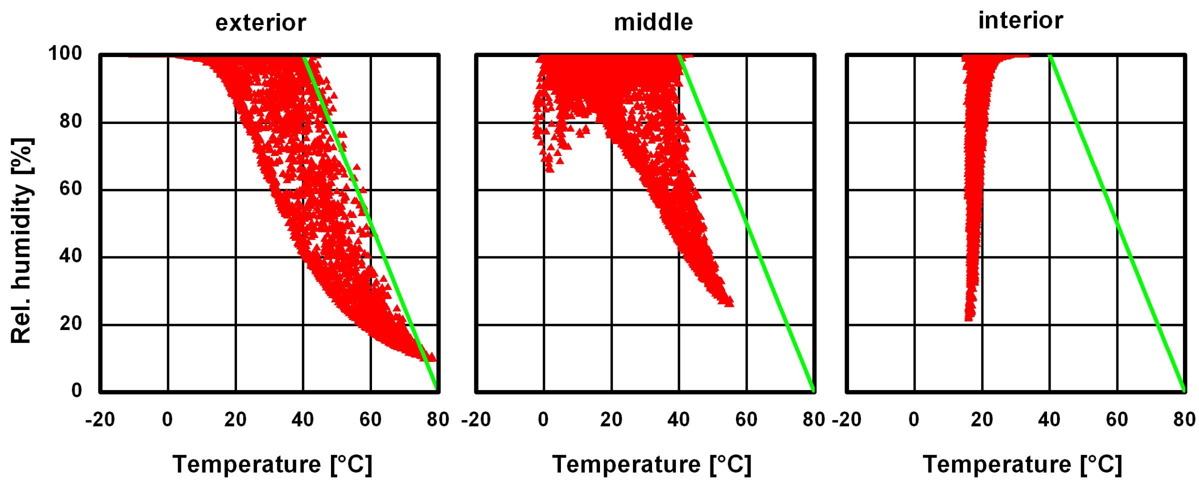

Figure 36: Coinciding temperature and humidity conditions on an hourly basis calculated at three monitor positions within the roof with 90 mm insulation located in Naples. The green line represents the limiting curve first defined in Figure 27.

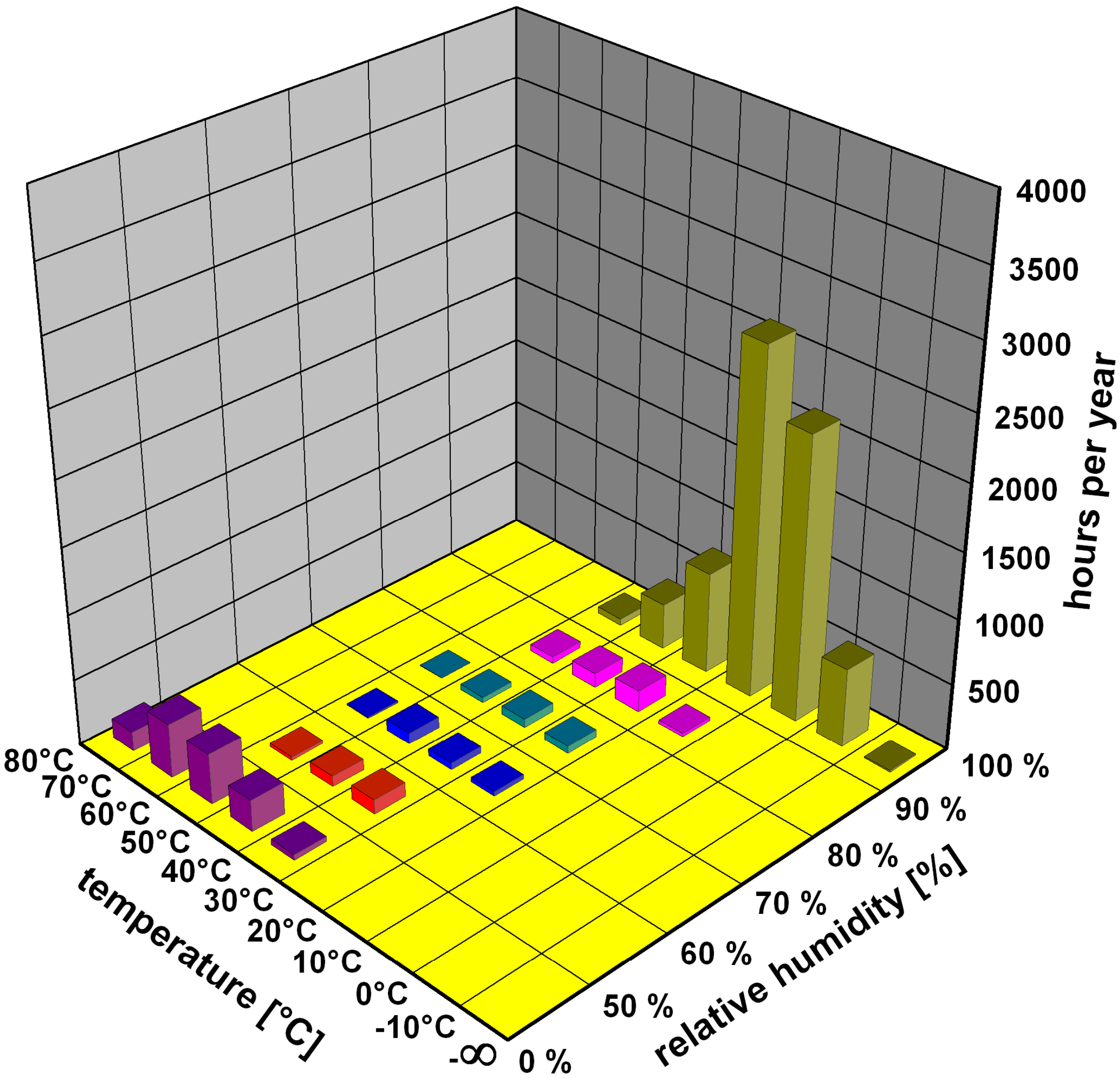

Figure 37: Classification of the coinciding temperature and humidity conditions at the exterior surface of the 90 mm glass fibre insulation for the climate in Naples.

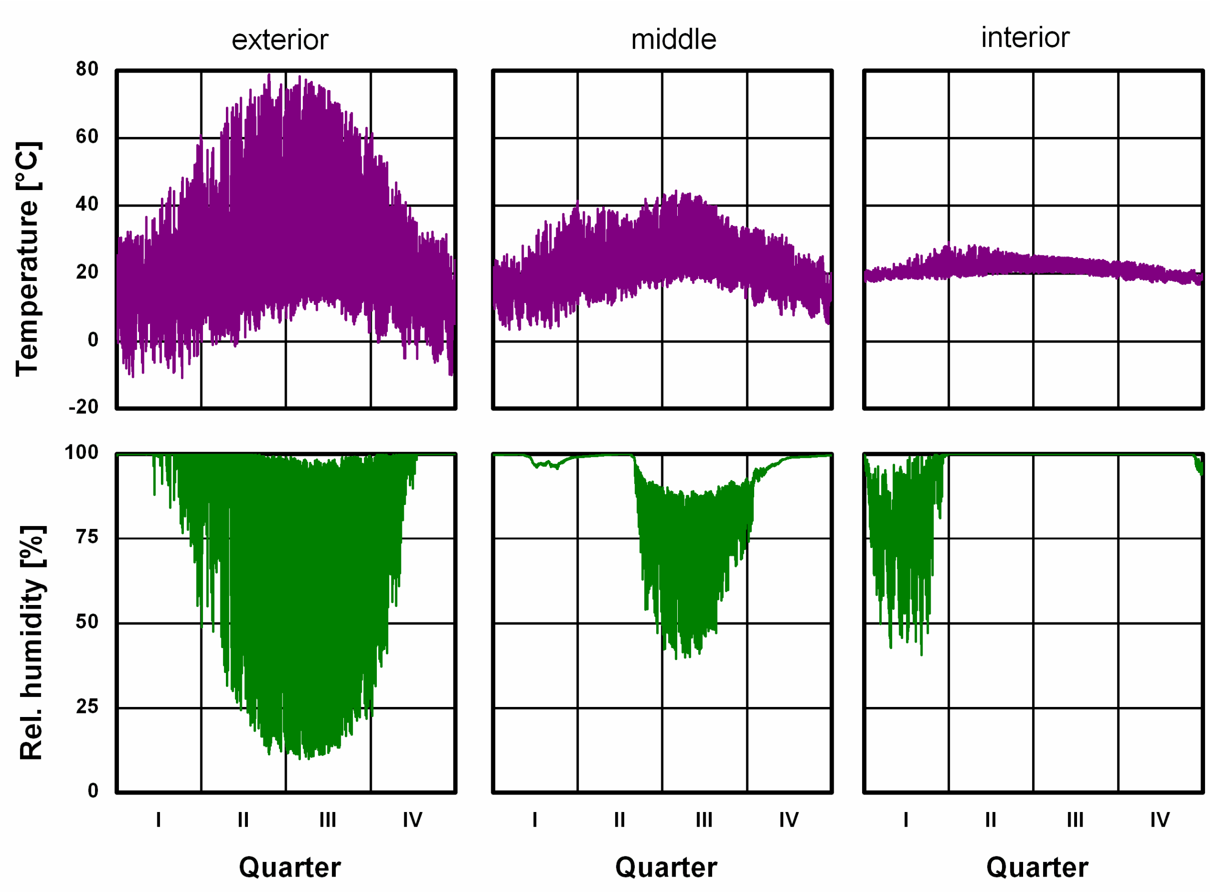

Figure 38: Calculated temperature and humidity conditions at different positions within a flat roof with 175 mm glass fibre insulation in Naples.

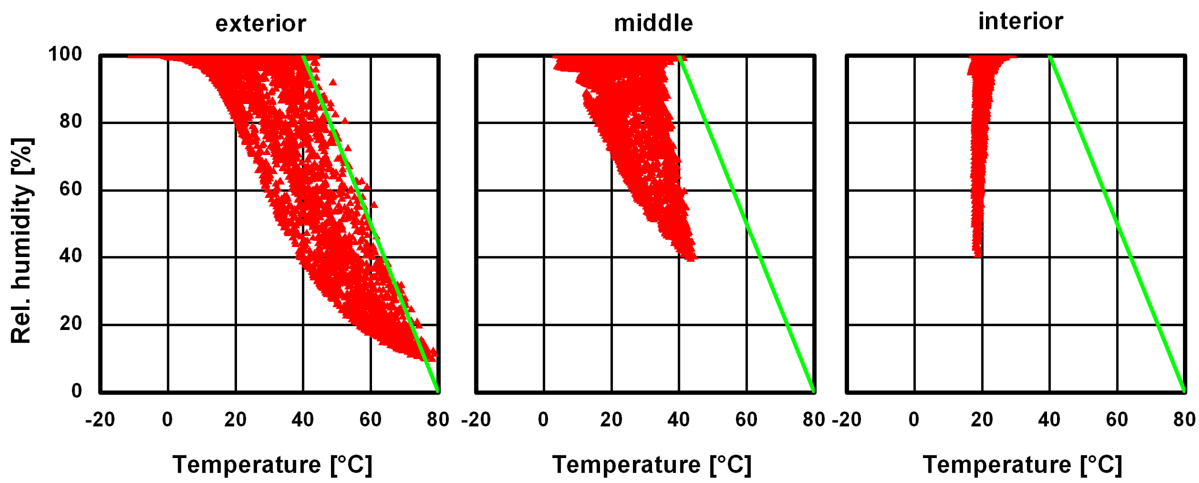

Figure 39: Coinciding temperature and humidity conditions on an hourly basis calculated at three monitor positions within the roof with 175 mm insulation located in Naples. The green line represents the limiting curve first defined in Figure 27.

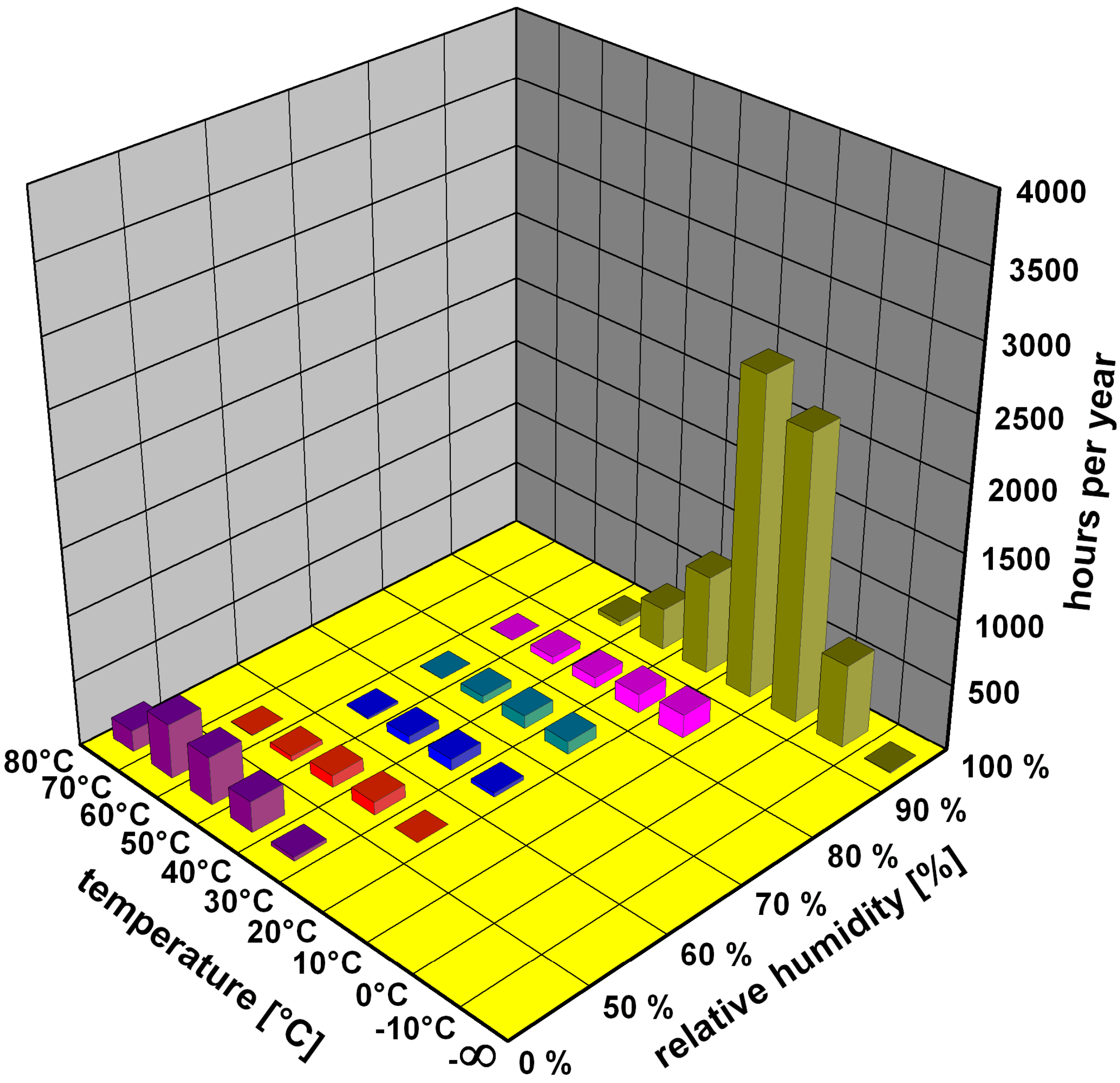

Figure 40: Classification of the coinciding temperature and humidity conditions at the exterior surface of the 175 mm glass fibre insulation for the climate in Naples.