Proceedings **Cold Climate HVAC**
Sisimiut, Greenland, 16-19 March 2009

Flat Roofs in Cold Climates - Climatic Limits for Building Flat Roofs with a Permeable Vapour Retarder

Christian Bludau[1,*], Hartwig M. Künzel[1]

[1]Fraunhofer Institute for Building Physics, Department of Hygrothermics, Germany

[*]*Corresponding email: christian.bludau@ibp.fraunhofer.de*

SUMMARY

Building in cold climate zones requires a high insulation thickness and a good protection against interstitional condensation. Applying vapour tight membranes on both sides of a roof construction offers no drying potential in case of leakages or initial moisture. Therefore the use of slightly permeable membranes at the interior side is often preferred because they allow condensed or existent moisture to dry out. However, drying to the interior space will only happen if the solar heat gains of the roof are high enough to inverse the vapour flow for a sufficient time period. This paper looks to the climate limits of building flat roofs with moderately permeable vapour retarders.

The balance of interstitial condensation and subsequent drying is investigated using an adapted hygrothermal simulation tool for heat and moisture transport in building components. For the simulations a black surfaced flat roof construction with mineral fibre insulation and moderate vapour retarder is considered. Special interest is set on the drying potential in relation to the building's location in Northern climate zones. The results can be shown by two limit lines around the North Pole, one for vapour retarders with a constant permeability and the other for those with humidity controlled permeability. These lines are not parallel to the Arctic Circle. They reflect the regional climate conditions which are influenced by the Gulf Stream and other meteorological phenomena.

KEYWORDS

flat roof, interstitional condensation, vapour retarder, climatic limits, drying potential

INTRODUCTION

Lightweight flat roof constructions with vapour tight membranes to both sides can theoretically be build in every climatic zone, if a tight seal against any type of moisture entry is guaranteed. Providing such a long-term guarantee is very difficult, therefore it often makes more sense to design constructions, which can dry out to the inside. The prerequisites for the drying process include an adequate vapour drive to the interior space, which only occurs when the roof's exterior surface temperature is high enough and a moderate vapour retarder that allows some vapour penetration. The aim of this paper is to investigate the hygrothermal performance of a roof construction with two different vapour retarders at the inside in order to determine the limits of such assemblies in northern countries regarding the risk of damage due to interstitional condensation.

FUNDAMENTALS

Lightweight flat roof construction and hygrothermal behaviour

Lightweight flat roof constructions only consist of an insulation layer between rafters or a similar construction. These constructions can be closed to the in- and outside using a vapour tight membrane. Then, theoretically, no moisture loaded air can enter the construction and no interstitional condensation will occur. In reality many of these constructions have small leakages (caused by small imperfections, staple holes, etc.), which allow the air to intrude, condensate and can lead to a slow accumulation of moisture. Also leakages in the roofing membrane can cause water to enter the construction. In tight construction this water is trapped, there is no chance of drying out. A more robust design can be achieved by replacing the vapour barrier or the roofing membrane by a membrane with certain permeance. At the outside this will only work properly, if there is no permanent layer of water on the roof, which is not always guaranteed in case of flat roofs. Therefore, the better way will be using a permeable membrane to the inside. Such a roof will dry out, if the annual moisture flow balance is negative, i.e. evaporation exceeds condensation. Vapour flow towards the interior is influenced by the exterior surface temperature of the roof, which depends on several factors. When the solar radiation hits the roof's surface, a part is reflected, another is absorbed. Some of the received energy is emitted back to the sky as infrared radiation and some is exchanged with the environment by convection. The remaining energy heats up the roof and may start the drying process.

Permeable membranes and humidity controlled permeability

A vapour retarder is specified by its vapour permeance or resistance. A common definition of the vapour diffusion resistance is the thickness of an airlayer with equivalent resistance, the so-called s_d-value given in meters. Most membranes have a constant permeance over the whole range of humidity. However, there are also some membranes available, which have a variable permeance, depending on the humidity of the ambient air. These so-called smart vapour retarders were developed for increasing the drying potential to the inside in roof constructions which are vapour tight to the outside. In Figure 1 permeance and s_d-value of such a vapour retarder are displayed as a function of relative humidity.

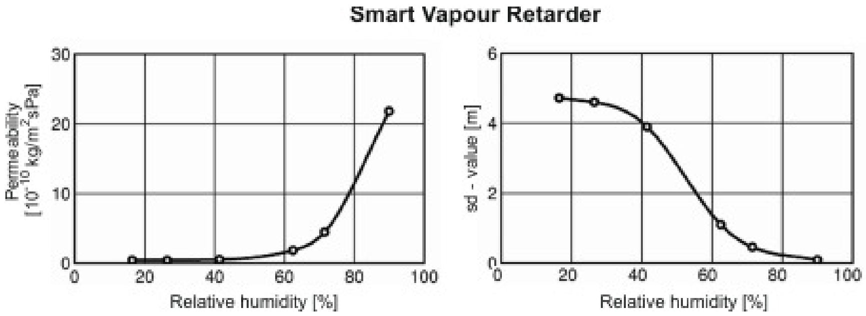

Figure 1. Permeance and s_d-value of a smart vapour retarder (PA film) as function of relative humidity.

METHODS

For investigating the climatic limits a lightweight flat roof construction with a dark surface and an insulation layer of 25 cm is selected. From inside to outside the construction consists of gypsum board, vapor retarder and mineral wool insulation with a thickness of 25 cm. On the top there is a wooden sheathing and the construction is closed with a roofing membrane with a s_d-value of 50 m (see Figure 2).

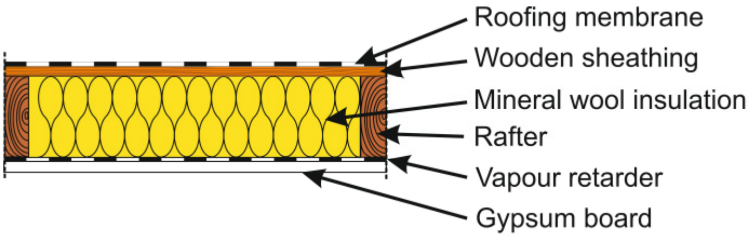

Figure 2. Lightweight flat roof construction

Two construction variants are considered, one with a moderate vapour retarder ($s_d = 3$ m) and the other contains a smart vapour retarder, where the s_d-value ranges between 0.1 m and 4.4 m (see also Fig. 1).

Using this construction, hygrothermic simulations are performed with a validated method for simultaneous calculation of heat and moisture transport in building components, called WUFI® (Künzel 1994). The construction part is modeled using material properties from the WUFI® material database. For the interior climate behavior specifications from WTA (2004) for 'normal moisture load' are used. The indoor conditions vary between 20 and 22 °C, respectively 40 and 60 % RH. The courses of the interior conditions are shown in Figure 3.

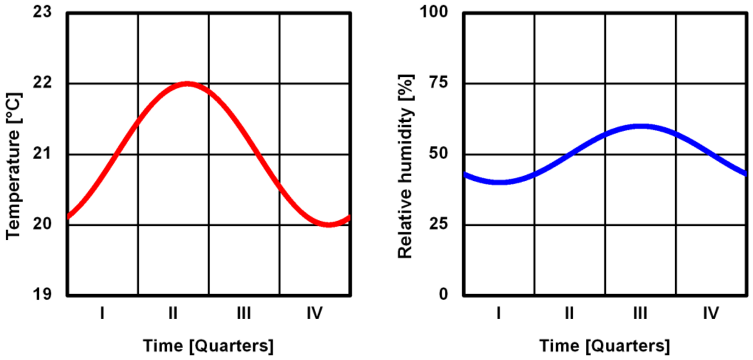

Figure 3. Interior climate conditions for normal moisture loads according to WTA (2004)

As exterior boundary conditions, the climatic reference data (hourly values) from the investigated location are used. The data are taken from the WUFI® Climatic Database and completed by climate data files generated with Meteonorm (2007). All data-sets contain hourly values for temperature, humidity, rain, wind, solar-, atmospheric radiation, etc.. For the investigation more than 40 climate locations where selected (see also Table 1). To consider the temperature caused by radiation, a short wave absorptivity of 0.8 (black surface) and a long wave emissivity of 0.9 (most non metallic surfaces) were used. The simulation software is able to calculate the explicit radiation balance (Kehrer et al. 2008), which includes overcooling effects due to radiation to the clear sky. The inclination of the roof is 0° (horizontal).

To assess the hygrothermal behaviour of the roof construction under different climates, the total water content as well as the water content in the wooden sheathing was examined. The value of the total water content is not significant but the tendency shows if there is water accumulating in the construction or if the construction has enough potential to dry out. The course of the water content in the wood should not exceed 20 percent by mass which is defined as safety limit in German standards DIN 68800 (1996) to avoid damage by rot or mould growth.

RESULTS

Exemplarily the result analysis is displayed for the three climatic locations Lund, Trondheim and Tromsø. Figure 4 shows the course of the total water content in the two construction variants as well as the course of the water content in the wooden sheathing. Employing the climate data of Lund, the temporal variations of the total water content in the construction show for both variants decreasing moisture levels during the first summer. Afterwards the seasonal moisture fluctuations remain well below the initial conditions. In Trondheim the variant with the PA vapour retarder shows a similar behaviour but the moisture is drying out slower. The variants with 3m vapour retarder in Trondheim and PA vapour retarder in Tromsø do not dry out sufficiently and the average water content slowly increases. The construction with the 3m vapour retarder in Tromsø shows a clearly increasing course. All the courses of the water content in the wooden sheathing show the same behaviour. Here the limit criterion (20 percent by mass) is exceeded for more than half a year. Both constructions in Lund and the construction with the PA retarder in Trondheim have its maximum values lower than 16 percent by mass. The values of the construction with the retarder with 3m in Trondheim and with the variable retarder in Tromsø do not clearly increase, but they exceed 20 percent by mass annually for more than half a year. The construction with the 3m retarder in Tromsø shows a strongly increasing development. Here the maximum water content in the wooden sheathing exceeds 38 percent by mass after about four years. This means the construction will fail in such a climate. In summary it can be concluded that the flat roof will work in Lund with both kinds of vapour retarder, while only the variant with PA retarder can be recommended for Trondheim. In Tromsø both construction variants appear inappropriate.

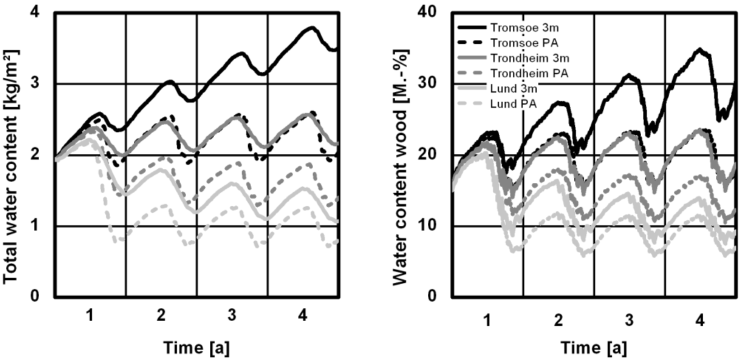

Figure 4. Example of the simulation results in Lund, Trondheim and Tromsø. The left diagram shows the total water content variations of the constructions and the right diagram the moisture fluctuations of the wooden sheathing.

In the same way the performance of the construction variants were evaluated for all locations displayed in Table 1. The table shows the climatic locations with minimum, mean and maximum temperatures, yearly sum of solar radiation and the applicability of the construction variants. The drying potential is influenced by the roof surface temperature, which mainly depends on the outdoor temperature and the solar radiation. The floating monthly mean value of the surface temperatures at all locations is displayed in the two diagrams in Figure 5. At locations, where both constructions work, the monthly mean value of the surface temperature is high during the summer and the maximum reaches more than 23 °C. During winter time the minimum mean surface temperatures do not fall below -10 °C in the Scandinavian countries and about -15 °C in North American countries. At locations, where none of the two construction variants works, the maximum mean temperature in summer does not exceed 17 °C in North America and 20 C in Scandinavian countries. At these locations, the yearly sum of global radiation is also very low (see Table 1). The mean surface temperatures of the locations where only the variant with smart vapour retarder will work lie somewhere in between.

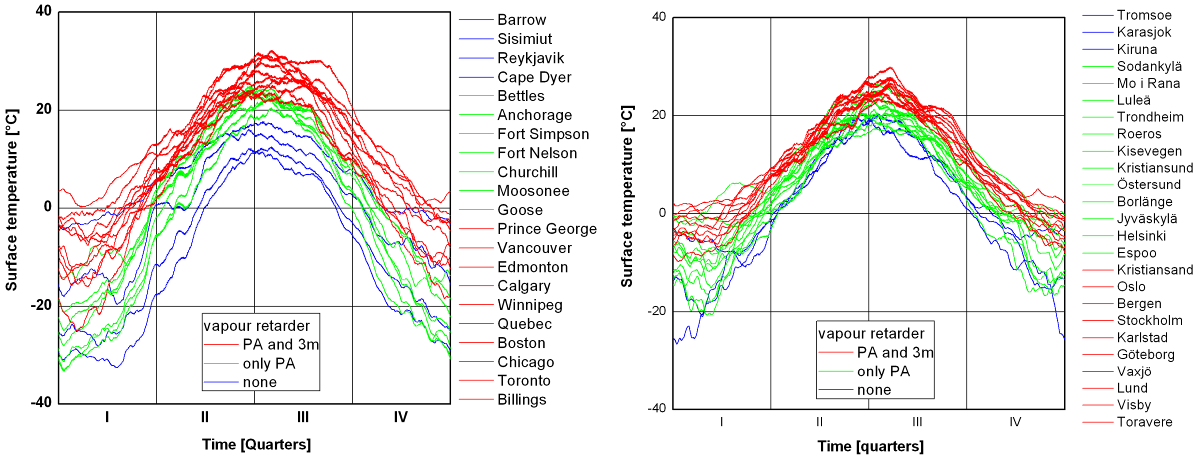

Figure 5. Surface temperature displayed as monthly floating mean values over one year.

Table 1. Simulated climatic locations.

Location	Min. Temperature [°C]	Mean Temperature [°C]	Max. Temperature [°C]	Sum of global radiation [kWh/m²a]	Smart Vapour Retarder	Vapour Retarder 3m
Tromsø (NO)	-14,2	2,1	22	679	-	-
Karasjok (NO)	-44,2	-3,1	24	715	-	-
Kiruna (SE)	-41,4	-1,7	25,1	811	-	-
Sodankylä (FI)	-40,2	-0,8	25,5	755	-	+
Mo i Rana (NO)	-20,2	3,3	25,6	679	-	+
Luleå (SE)	-43,4	1,2	27,2	877	-	+
Trondheim (NO)	-13,8	5,4	24,2	734	-	+
Røros (NO)	-41,7	-0,9	24,2	695	-	+
Kise på Hedmark (NO)	-25,2	4,6	26,5	840	-	+
Kristiansund (NO)	-6,4	7,7	25	658	-	+
Östersund (SE)	-39	1,5	27,2	905	-	+
Borlänge (SE)	-31,4	4,5	28,9	929	-	+
Jyväskylä (FI)	-34,8	2,8	27,5	833	-	+
Helsinki (FI)	-30	4,3	28,5	-	-	+
Espoo (FI)	-25,2	5,5	28,4	870	-	+
Kristiansand (NO)	-16,3	7,3	24	905	+	+
Oslo (NO)	-14,8	6,8	29,3	866	+	+
Bergen (NO)	-9,7	8,1	28	840	+	+
Stockholm (SE)	-18,6	6,8	29,4	999	+	+
Karlstad (SE)	-23,8	5,6	28,3	949	+	+
Göteborg (SE)	-12,2	8,8	27,8	922	+	+
Vaxjö (SE)	-17,7	7,1	28,5	934	+	+
Lund (SE)	-10,1	9,2	28,3	1016	+	+
Visby (SE)	-8,3	8,4	27,6	1082	+	+
Toravere (EE)	-24,3	5,3	29,3	961	+	+

Location	Min. Temperature [°C]	Mean Temperature [°C]	Max. Temperature [°C]	Sum of global radiation [kWh/m²a]	Smart Vapour Retarder	Vapour Retarder 3m
Sisimiut (GL)	-32,7	-3,8	11,9	940	-	-
Reykjavik (IS)	-12,4	4,3	17	772	-	-
Barrow (US-AK)	-42,4	-12,4	17,7	721	-	-
Cape Dyer (CA)	-36,8	-10,1	14,6	962	-	-
Bettles (US-AK)	-45,9	-5,4	27,7	875	-	+
Anchorage (US-AK)	-29,4	0,8	23,9	870	-	+
Fort Simpson (CA)	-44,2	-3,5	28,5	866	-	+
Fort Nelson (CA)	-38,6	-1,2	30,1	1057	-	+
Churchill (CA)	-40,4	-7,1	28,7	1113	-	+
Moosonee (CA)	-38,4	-1,2	32,1	1189	-	+
Goose (CA-NL)	-31,5	-0,1	32,6	1077	-	+
Prince George (CA)	-33	3,8	28,7	1134	+	+
Vancouver (CA)	-11,1	9,1	27,2	1174	+	+
Edmonton (CA)	-40	2	28	1260	+	+
Calgary (CA)	-36,7	2,5	30,6	1347	+	+
Winnipeg (CA)	-45	1,2	33,9	1372	+	+
Quebec (CA)	-31,7	3,6	29,4	1228	+	+
Boston (US)	-20	9,7	32,8	1440	+	+
Chicago (US)	-22,8	8,8	34,4	1456	+	+
Toronto (CA)	-23,3	6,7	32,8	1367	+	+
Billings (US)	-23,9	6,8	36,7	1511	+	+

The resulting limit curves for the applicability of the two roof construction variants are plotted in two maps, displayed in Figure 6, one for North America and one for Scandinavia. In Scandinavia the limit curves coincide with the northern parallels. The limit for the vapour retarder with 3m is close to the 60° parallel and the limit for the construction with the variable vapour retarder runs close to the 67° parallel. In the coastal areas of Norway the limit curves are shifted to the north because of the effects of the Gulf Stream. In North America the limit curves start in the west as well as in the Scandinavian countries close to 60° North for the 3m retarder construction and somewhere close to the 67° parallel the variant with smart vapour retarder, but then they drift to the south, probably as a result of the colder continental climate. The limit curves end in the east close to the 48° respectively 60° parallel. In Sisimiut (Greenland) and Rejkjavik (Island) none of the two construction variants will work.

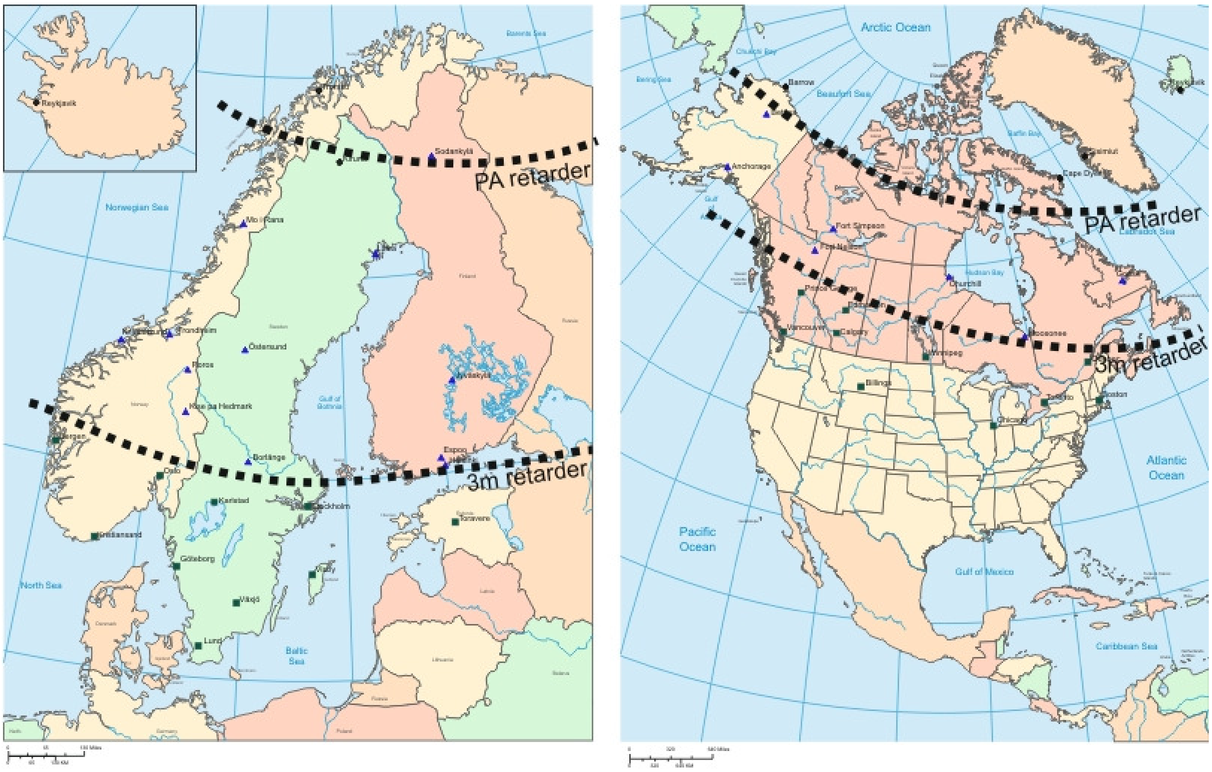

Figure 6. Limit curves for the applicability of the construction variants with the two different vapour retarders in Scandinavia and North America.

DISCUSSION

In this paper climate limits for the application of flat roofs with drying potential towards the interior have been determined by hygorthermal simulations. Special interest is set on the drying potential in relation to the building's location in Northern climate zones. The results show two limit curves around the North Pole, one for flat roof constructions with moderate vapour retarders (s_d = 3 m which is equivalent to a permeance of 1 U.S.-perm) and the other with a smart vapour retarder whose permeance is humidity controlled. These curves are not parallel to the Arctic Circle. They reflect the regional climate conditions which are influenced by the Northern Atlantic Currents and other meteorological phenomena. In the area between the two limit curves only constructions with a smart vapour retarder should be considered. Although the maximum s_d-value of this retarder is not much higher compared to the other retarder, it offers a considerable higher drying potential.

The limit curves should only be taken as a tentative recommendation. This means a separate hygrothermal assessment should be carried out for any particular roof design, especially when the specific location is close to these limit curves. The limits predominantly are usable for the investigated construction, with 25 cm insulation layer and a black surface. The color of the surface is important (Bludau et al. 2008), because of the energy absorbed from solar radiation. Intensity and angle of solar radiation decreases with rising latitude. The thickness of the insulation layer has an influence on the water content. More insulation layer results in higher water content levels of the wooden sheathing.

CONCLUSIONS

The problem of moisture trapped in flat roofs with vapour barriers has helped to promote more moisture tolerant design where the vapour barrier is replaced by a moderately permeable vapour retarder. However the applicability of roof constructions with drying potential towards the interior is subject to climate dependent limitations. The limit curves defined in this paper represent the most Northern locations where the investigated roof constructions are at the brink of failure. In order to keep a safety margin the location of the specific roof should not be too close to these limit curves. In order to keep the construction comparable at the different locations, the interior climate was chosen according to the WTA (2004) recommendations, which uses conditions with a sine curve over the seasons as shown in the figure 3. The functionality of the construction highly depends on the interior climate and the used climate is not necessarily the best assumption for really cold climates. Extra simulations were carried out, using an interior climate according to the EN 15026 (2007) standard, where the interior climate is generated depending to the exterior temperature. The values are slightly lower than the sine curve from WTA and so they could be more realistic in cold climate regions. A comparison of the climate according to EN in Tromsoe, Reykjavik and Sisimiut with the WTA conditions is shown in Figure 7.

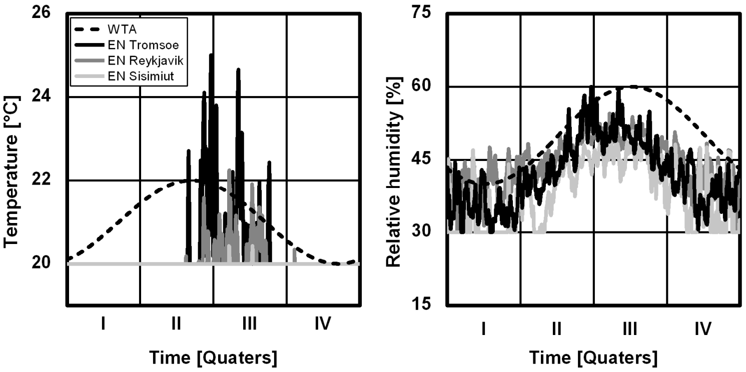

Figure 7. Comparison of the interior climate according to WTA and EN 15026 in Tromsoe, Reykjavik and Sisimiut. The interior climate in EN 15026 is a function of exterior air temperature.

Figure 8 shows the water contents at the three locations with the WTA interior climate and the one created according to EN 15026. At all three locations the assumptions for the interior climate show a lower relative humidity for the EN and therefore the water content is lower with these climates. The construction with the smart vapour retarder to the inside can be used at these locations by using the EN conditions. This shows that if the prevailing indoor conditions are known a lower relative humidity can be used as base for the calculations. The gained limit curves for the 3m retarder and the PA retarder will move further up to the north. By calculating according to the WTA recommendations, the results include a larger safety factor.

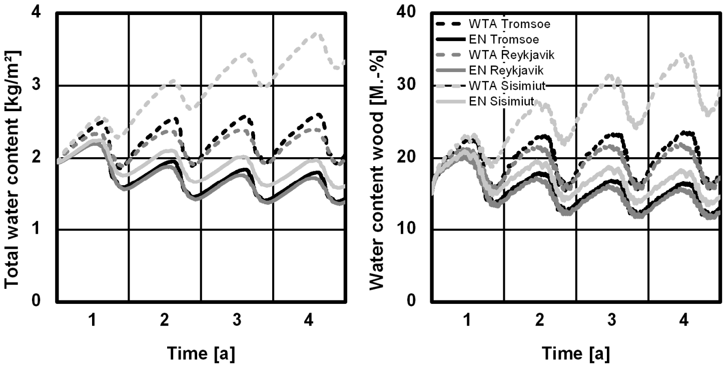

Figure 8. Total water content and water content in wooden sheathing for the locations Tromsoe, Reykjavik and Sisimiut with two different interior climatic behaviors.

In any case it makes sense to confirm the applicability of a particular roof construction by performing a hygrothermal analysis. It is equally important to make sure that the situation at the construction site (exposure, local environment, shading) and the expected operation of the building correspond to the boundary conditions employed for the transient calculations.

REFERENCES

Bludau Ch., Zirkelbach D., Künzel, H.M. 2008, Condensation Problems in Cool Roofs, Proceedings of the 11th International Conference on Durability of Building Materials and Components, Istanbul, Turkey, pp. 1065-1072

DIN 4108:2001, *DIN Standard 4108-3*, Wärmeschutz und Energie-Einsparung in Gebäuden. Deutsches Institut für Normung, Beuth Verlag, Berlin

DIN 68800:1996, *DIN Standard 68800-2*, Holzschutz – Vorbeugende Bauliche Maßnahmen im Hochbau. Deutsches Institut für Normung, Beuth Verlag, Berlin

EN 15026:2007, Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation; European Committee for Standarfization, Brussels

Kehrer M. and Schmidt, Th. 2008. Radiation Effects On Exterior Surfaces. Proceedings of the 8th Symposium on Building Physics in the Nordic Countries. Copenhagen, Denmark, pp. 207-213

Künzel H.M. 1994, Simultaneous Heat and Moisture Transport in Building Components. One- and two dimensional calculation using simple parameters. *Ph.D. Thesis*, University of Stuttgart. 68 pages.

Meteonorm 2006, METEONORM 6.0 (Edition 2007), Comprehensive meteorological reference, incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location in the world. http://www.meteonorm.com

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