Thermal Bridges of Modern Windows—Experience with Minimum Acceptable Surface Temperature

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ABSTRACT

With its focus on reduced energy consumption, contemporary housing construction requires a highly insulated and airtight building envelope with as few thermal bridges as possible. Windows must be carefully designed, as thermal bridges can lead to surface condensation or mold growth, even if the window has an U-factor of 1 W/(m^2·K) or lower.

This paper describes the development of modern, energy efficient Danish windows with reduced thermal bridges. It focuses on materials, geometry, and sealing of window panes based on a literature review. Examples of modern windows are presented. Experience with the minimum acceptable surface temperature regarding surface condensation or mold growth, implemented in the Danish Building Regulations in 2010 (Danish Enterprise and Construction Authority 2010), and the calculation method for this temperature based on international standards is discussed.

The introduction of the minimum acceptable surface temperature has been an important driver for the development of new window solutions in Denmark, increasing the inner-surface temperature at the sealing of window panes. However, it will not stop complaints from consumers, as this temperature is calculated under standardized conditions. Increasing requirements for airtightness increases the importance of sufficient ventilation in order to prevent problems with condensation or mold growth.

INTRODUCTION

Contemporary housing construction focuses on reducing energy consumption. This means that the building envelope has to be highly insulated and airtight with as few thermal bridges as possible. The surface temperature becomes lower at thermal bridges than at surrounding surfaces. Indoor air that gets in contact with the surface at the thermal bridge will be cooled down resulting in a higher relative humidity. This means that the relative humidity is higher at thermal bridges than at other surfaces.

Windows are normally the coldest area in a room and previously the presence of dew on windows was used as an indication that the room was insufficiently ventilated. The pane of traditional double-glazed windows or coupled sashes was previously the coldest area of a window. However, the corners of the sash and the edge of the glazing are normally the coldest parts of windows with low-e glazing (Brandt 2013).

To minimize the thermal bridges, windows must be carefully designed. Otherwise it will lead to moisture-related problems such as condensation, degradation, or mold growth even if the window has a total U-factor of 1 W/(m^2·K) or lower.

Condensation occurs when the surface temperature is lower than the dew-point temperature, which is given by the moisture content in the ambient air. Even at higher temperatures, there might still be a risk of moisture problems, as molds are known to grow at a relative humidity as low as 75%, depending on the temperature and material (Sedlbauer 2001). Therefore, to prevent mold growth, a critical surface temperature may not only be based on the risk of condensation (100% rh) but also based on a lower moisture level, e.g., the minimum acceptable surface temperature should be higher than the dew-point temperature.

The present requirement for U-factors for windows means that some of the problems that previously were

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common are not found in contemporary constructions (Brandt 2013). For instance, condensation is very rare on the center of modern glazing with a U-factor of 1 W/(m^2·K) or lower. However, windows should not be characterized by energy performance alone. Acceptable moisture levels must be ensured as well. The paper discusses the minimum acceptable surface temperature as a parameter and the method for calculating this based on the building legislation and experience gained with windows in Denmark. The minimum acceptable surface temperature approach is relevant for a major part of Europe situated in the same warm temperate, fully humid climate zone, defined by the Köppen-Geiger climate classification (Kottek et al. 2006).

The development of modern, energy-efficient windows in Denmark is described, highlighting the necessary choices that had to be made concerning materials and design. Examples of modern windows are shown. Then the energy and moisture-related requirements for windows in the Danish Building Regulations (DBR) are described, as these have been an important driver for the development of windows. The moisture-related requirements are based on an international standard for calculating the minimum acceptable surface temperature for mold growth or surface condensation, which is briefly described (ISO 2012b). Examples of using the standard in a Danish context are given as a background for discussing the method itself and its practical consequences. The choice of level for the minimum acceptable surface temperature is also discussed.

DEVELOPMENT OF ENERGY-EFFICIENT WINDOWS

A window is a complex construction where different parts all contribute to the total U-factor: the glazing, the sash/frame construction, and the edge sealing. Since 2000, research conducted at the Technical University of Denmark, financed by the Danish Energy Agency, has aimed at inspiring and helping the Danish window industry and it has been an important background for the development of modern, energy-efficient windows. Development was necessary to comply with the gradually-tightening requirements for the energy performance of windows and recently also the requirement concerning the avoidance of surface condensation as presented in the section "Requirements for Windows in the DBR."

U-factor for Glazing

As glazing constitutes the major part of a window area, the first efforts at reducing the U-factor of windows focused on reducing the U-factor of the glazing by increasing the number of layers of glazing, by filling the space between panes with gas instead of air or by applying low-emission coating. Table 1 shows some typical U-factors for different types of glazing (Nielsen 1991).

While condensation on the inside of the glazing was common on windows with a high U-factor, improved U-factors of the glazing have resulted in condensation on the outside instead. This condensation can occur on clear nights with humid air (above 85% rh), usually in the spring and autumn, and in locations where the window has an unobstructed view of the sky. Since the outbound heat transport through the window is small, the outer pane thus becomes colder than the surrounding air, and condensation will form. The condensation starts to form at the bottom of the pane (the coldest part), and in some cases it spreads over the whole pane (Persson et al. 1994).

Table 1. U-factors for Different Types of Glazing, All with 4 mm Glass and 12 mm Distance between the Layers of Glazing, Except when Noted (Nielsen 1991)

Type of Glazing	Type of Glass	U-factor (Center) W/(m^2·K)
Double glazing	Clear pane	2.9
Double Low-e glazing	Same + pane with a Low-e coating	1.9
Aerogel 20	Two clear panes with 24 mm distance, space filled with Aerogel	0.6
Aerogel 30	Same with 34 mm distance	0.4

Materials for Sash/Frame Construction

Improvement of the U-factor of glazing resulting in U-factors below 1 W/(m^2·K) meant that it became important to reduce the U-factors of the sash/frame construction. Development of new constructions has taken place for several years involving different kinds of materials: wood (Finland, Sweden, and Denmark), aluminum (e.g., Denmark), polyvinyl chloride (PVC) (Germany), or glass-fiber reinforced polyester (GFRP) (USA and Canada) (BYG DTU 2009a; 2009b). Or a combination, e.g., where a traditional inner wood part is combined with a weather-resistant outer part made of aluminum or PVC as shown in Figure 1.

Constructions made of aluminum, PVC or GFRP can be produced with a lot of cavities. Thereby the thermal conductivity can be reduced depending on the number and size of the cavities and whether the cavities are empty or filled with insulating material, etc. GFRP is stronger than PVC and this avoids the use of steel as reinforcement. Aluminum is strong and light, but it has a very high thermal conductivity (see Table 2). This makes it difficult to make sash/frame profiles of aluminum with a low U-factor without thermal interruption and the only real solution is to use another material, e.g., GFRP.

Design of Sash/Frame Construction

Reduction of the U-factor of the sash/frame construction often resulted in very large dimensions of the sash/frame part of the window. This in turn reduced the amount of solar radiation coming through the window and eventually reduced the

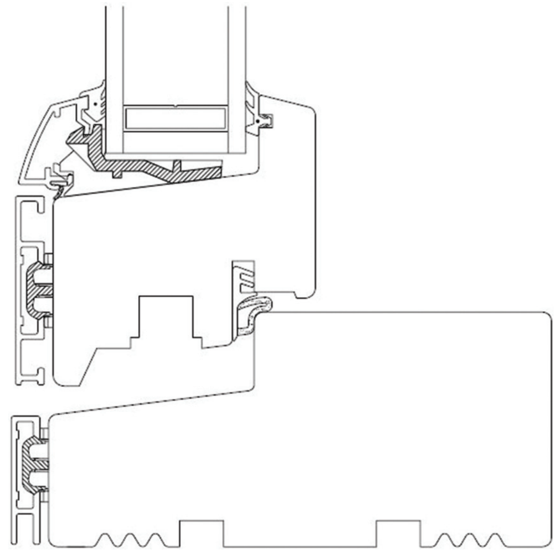

Figure 1 *Wood sash/frame construction with an outer cover of aluminum (BYG DTU 2001). External side to the left.*

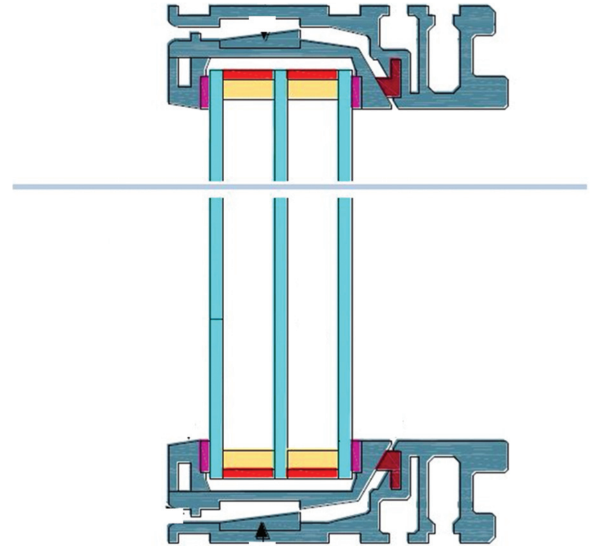

Figure 2 *Detail from a window with a sash/frame construction of GFRP, designed to optimize the glass area of the window,* U_w *= 0.78 W/(m*^{2}*·K),* E_{ref} *= 27 kWh/m*^{2} *(Kragh and Svendsen 2009). External side to the left.*

Table 2. Thermal Conductivity of Different Materials Used for Windows

Aluminum	Stainless Steel	PVC	GFRP
220 W/(m·K)	15 W/(m·K)	0.2 W/(m·K)	0.2–0.4 W/(m·K)

energy performance of the window, expressed by the net-energy gain, E_{ref}.

Therefore, attempts were made to develop windows with a reduced sash/frame ratio without increasing the thermal bridge at the edge sealing (BYG DTU 2009b; Kragh and Svendsen 2009). Such solutions are primarily relevant for dwellings and not for offices, etc., where there is a risk of overheating the building. Figure 2 shows a solution with a sash/frame construction made of GFRP with better energy performance than traditional Danish products with a net-energy gain of –60 to –40 kWh/m^2 (Kragh and Svendsen 2009; Applefield et al. 2010).

For a simpler solution based on traditional sash/frame constructions, it is suggested to place the sash construction on the external side of the frame construction (BYG DTU 2009b). Solutions with a sash construction on the external side of the frame construction (as shown in Figure 3) are produced for the Danish market by a number of manufacturers.

Design of the Edge Sealing/Construction

Concurrently with the development of new designs of the sash/frame construction, work has been done to reduce the linear-thermal transmittance (or equivalent thermal conductivity) of the edge construction between the panes and the sash. The equivalent thermal conductivity of different edge constructions is given in Table 3. The edge constructions consist

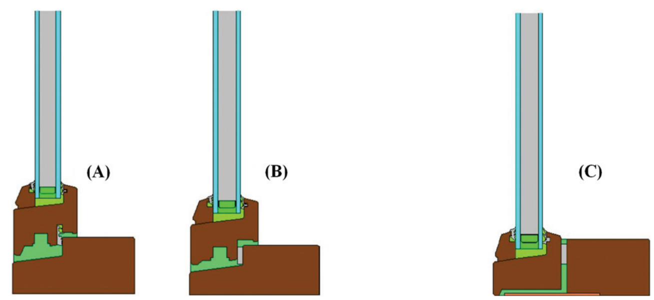

Figure 3 *A traditional design of (A) a wood sash/frame construction, (B) a slimmer profile and (C) a design where the sash is placed on the external side of the frame (BYG DTU 2009b). External side to the left.*

of a spacer that provides the construction with a specified stiffness and sealing materials (see Figure 4).

The total U-factor of the window can be reduced by up to 10% by using a spacer with a low equivalent thermal conductivity instead of using a profile made of aluminum. The improvement of a specific window depends on the size of the window, the design of the sash/frame construction, the type of glazing, etc.

Apart from improving the U-factor of the window, the choice of material for the spacer also affects the risk of condensation, as it affects the inner-surface temperature. The lowest inner-surface temperature of a traditional double-glazed window with a wood sash/frame construction, 15 mm distance between layers, and a spacer made of aluminum, is 8.2°C (BYG DTU 2009a), when the external and internal

Table 3. Equivalent Thermal Conductivity of Edge Constructions Depending on the Material Used for the Spacer in Windows with Double Glazing and 15 mm Distance between Layers (BYG DTU 2009a)

0.4 mm Aluminum Profile	0.2 mm Stainless Steel Profile	1 mm PVC Profile	Massive Polyisobutylene
2.6 W/m·K	0.7 W/m·K	0.5 W/m·K	0.3 W/m·K

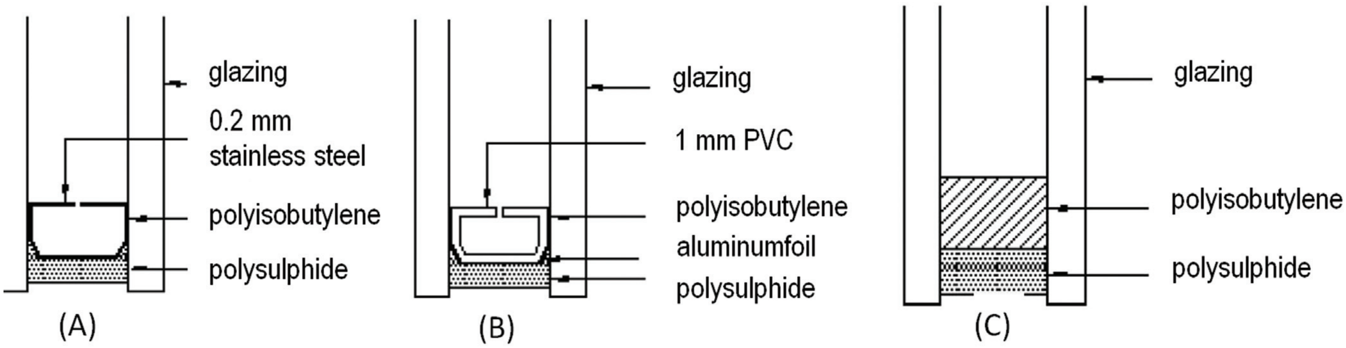

Figure 4 *Design of edge constructions for a window with double glazing. The spacer made of 0.4 mm aluminum, (A) 0.2 mm stainless steel or (B) 1 mm PVC is attached to the glass with a 0.25 mm polyisobutylene sealant and 3 mm polysulphide sealant in the bottom for extra mechanical stability. (C) Solution with a spacer of polyisobutylene (BYG DTU 2001; 2009a).*

Table 4. Lowest Inner-surface Temperature for Windows with a Wood Sash/Frame Construction and 12 mm Distance between Layers of Glazing, External and Internal Temperature –10°C and 20°C (Nielsen 1991)

Type of Glazing	θ_{si} Aluminum Spacer	θ_{si} Stainless Steel Spacer
Double glazing	4.3°C	7.0°C
Triple glazing	7.1°C	10.0°C
Low-e double glazing	5.2°C	8.7°C
Low-e triple glazing	8.8°C	11.7°C

temperature is 0°C and 20°C respectively. Lowest means that the inner-surface temperature refers to the location on inner-glass surface closest to the dew-point temperature of the indoor air. If the air change is 0.5 h^{-1} and the inhabitants produce 9.5 kg moisture per 24 h, the equivalent of 4–5 people, there is a risk of condensation 57 h/yr. By using a spacer made of stainless steel or PVC instead, there is a risk of condensation of only about 17 h and 11 h/y (BYG DTU 2001; 2009a). The number of hours with a risk of condensation should be as low as possible, but the result of condensation expressed as discoloring as well as rot and mold growth will of course depend on whether condensation takes place often, each time for a short period, or seldom, but for longer periods.

Table 4 shows the effect of using a spacer made of aluminum or stainless steel on the inner-surface temperature for traditional windows with a wood sash/frame construction and a 12 mm distance between the layers of glazing (Nielsen 1991).

The choice of spacer not only depends on its thermal conductivity. It is important that the spacer is tight and stays tight for the window's service life to prevent moisture from entering the construction or punctured glazing with resulting reduced insulating capacity. This is the reason for using a double-sealed unit, as shown in Figure 4. Other properties that are relevant: stiffness, ability to adhere to glass, that the spacer is easy to work on, and cost (Nielsen 1991). Altogether, this has for a long time made aluminum the best choice.

The durability of spacers made of aluminum is known to be good, while the durability of spacers made of PVC is unknown. The experience of spacers made of materials with a low-thermal conductivity has been gained over about 8 years. Today all windows for new buildings in Denmark have warm spacers made of stainless steel, polycarbonate, or a combination of stainless steel and polypropylene.

Examples of Modern Danish Windows

Table 5 shows examples of modern, openable Danish windows and their data that refer to the U-factor, the net-energy gain E_{ref}, and the lowest inner-surface temperature θ_{si} at 20°C (internal) and 0°C (external). Windows with similar properties for the U-factor and net-energy gain from other Danish manufacturers and from the USA, Canada, Germany, etc. can also be found. Windows on the Danish market seem to be the only ones with specifications for the inner-surface temperature. In the USA, the condensation resistance (CR) calculated according to the National Fenestration Rating Council is widely used by manufacturers as a relative indicator of the ability to resist the formation of condensation at a specific set of environmental conditions, however it is not mandatory (NFRC 2010).

Table 5. Examples of Modern, Openable Windows on the Danish Market. Layers of Glazing, Sash/Frame Material, U-factor, E_{ref}, Lowest Inner-surface Temperature (θ_{si}), and CR According to (NFRC 2010)

Type	Layers of Glazing	Sash/Frame, Material	U-factor W/(m^2·K)	E_{ref} (2) kWh/m^2	θ_{si} °C	CR
A1	2	Wood with aluminum cover (1)	1.36	–29	11.7	48
A2	3	Same	0.77	3	14.1	63
A3	3	Wood/GFRP	1.01	–17.2	13.5	59
B1 (3)	2	Wood/aluminum	1.6	–40	7.2	25
B2 (4)	2	Wood/aluminum with thermal interruption	1.4	–24	9.5	37
B3 (5)	2	Wood/GFRP	1.3	–17	10.3	41
C1	2	PVC	0.82	8	14.0	63
D1	3	Wood/PUR/alu	0.87	24	14.1	63

Notes: (1): Separated by a composite profile, (2): Existing requirement for net-energy gain in the DBR –33 kWh/m^2, (3): Marketed in 1985–2008, (4): Marketed since 2009, (5): Marketed since 2011.

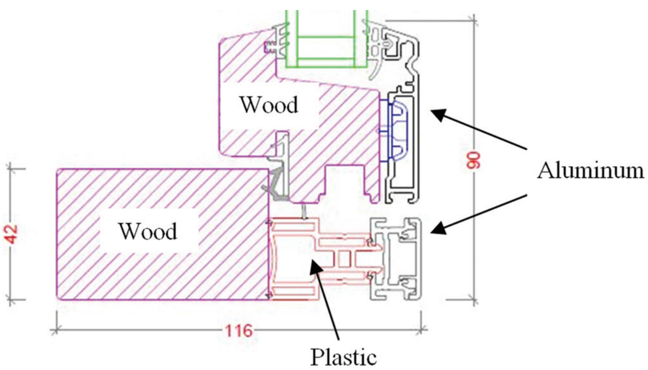

Figure 5 Design of window type A1. External side to the right. Measures in mm.

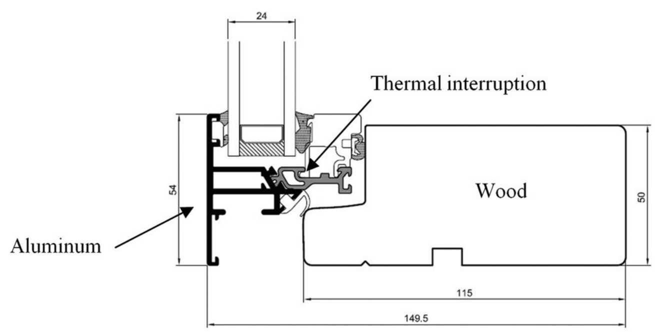

Figure 6 Design of window type B1. External side to the left. Measures in mm.

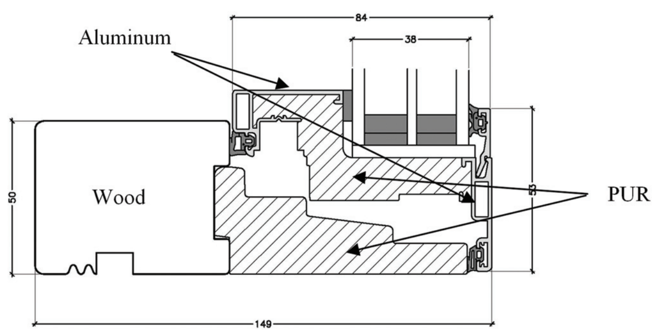

Figure 7 Design of window type D1. External side to the right. Measures in mm.

With one exception, (B1), all the windows in Table 5 have been marketed in Denmark since 2008 and later, and are produced with a warm spacer made of stainless steel, polycarbonate, or similar materials. Types A1–A3 are designed with a traditional mutual placement of the sash and frame construction, as shown in Figure 5. Types B1–B3 are designed with the sash construction placed on the external side of the frame construction, as shown in Figure 6, giving the optimal amount of solar energy.

Types C1 and D1 are examples of windows where the sash/frame construction is a combination of wood at the internal side and plastic (PVC or polyurethane [PUR]) at the external side, covered by a thin aluminium profile, as shown in Figure 7.

Type B1 resulted in condensation on the inner side of the window in many cases in Denmark, although the lowest inner-surface temperature of this window type is higher than 7°C, recommended since 2003 by the Association of Danish Window Manufacturers (2003). This shows that the recommendation was obviously too low. Type B1 also had a relatively high U-factor, which together with the low inner-surface temperature probably is the reason for removing it from the market.

Table 5 also shows CR for these windows. The calculation method described by the NFRC is based on 2D heat transfer simulation of the cross sections of the whole window and calculations are made separately for the frame, edge-of glazing and the center-of-glazing (2010). The resulting CR for the whole window is determined from the lower of these ratings. The values for Danish windows shown in Table 5 are the result of a simplified calculation based on the inner-surface temperature (θ_{si}). θ_{si} is adjusted as NFRC (2010) uses 21°C and –18°C as internal and external temperatures while θ_{si} is based on 20°C and 0°C.

As the inner-surface temperature in Table 5 represents the coldest spot on the window, a calculation of CR based on this value would underestimate CR compared with American windows, where the calculation is based on the conditions for the window as a whole. Instead a weighted calculation where 25% of the window (the lower part) is represented by the inner-surface temperature given in Table 5 and the other 75% of the window is represented by a 1°C higher temperature according to (BYG DTU 2001). It is assumed that the inner-surface temperature given in Table 5 represents the worst case, i.e., no separate calculations are made for frame, edge-of-glazing, or center-of-glazing.

The values for CR calculated for the Danish windows are comparable with values for windows in the USA, according to the NFRC Certified Products Directory (search.nfrc.org). As the calculation of CR for Danish windows is based on simplified conditions, no further discussion on specific differences in CR for windows with two or three layers of glazing is made in this paper.

REQUIREMENTS FOR WINDOWS IN THE DBR

Since 1966, minimum requirements for windows in new buildings were expressed by U-factor in the DBR (Ministry of Housing 1966) and they were gradually tightened from 3 W/(m^2·K) in 1966 to 1.5 W/(m^2·K) in 2008. It was also prescribed that thermal bridges in windows must be insignificant. A requirement for U-factor at the replacement of windows was introduced in 2006 (Danish Enterprise and Construction Authority 2006).

Although a window is considered to be energy efficient if it has a low U-factor, that is not sufficient to describe a window's energy performance, as it can have a very low U-factor, while more or less neglecting another important property, e.g., the amount of solar radiation through the glazing. Therefore, the minimum requirement for windows both in new buildings and at replacement has since 2010 been expressed by the net-energy gain through the window in the heating season: –33 kWh/m^2 per year for vertically-oriented windows (Danish Enterprise and Construction Authority 2010). The net-energy gain E_{ref} is based on the U-factor U_w and the solar energy transmittance of the window g_w expressed as

$$E_{\text{ref}} = I \cdot g_w - G \cdot U_w = 196.4 \cdot g_w - 90.36 \cdot U_w \quad (1)$$

The solar heat gain I and the number of degree hours G during the heating season are determined on the basis of the Design Reference Year DRY (Lund 2001). The solar heat gain through windows depends on the orientation of the windows. A single-family house with the following distribution of windows is used as a point of reference: north 26%, south 31%, east/west 33%. The calculation uses an opening reference window 1.23 × 1.48 m.

The Danish standard DS 418 (Danish Standard Association 2011) on the calculation of the heat loss from buildings has been part of the Danish construction legislation since the first national Building Regulations was implemented (Ministry of Housing 1961) and it specifies how the U-factor for windows is calculated. In the newest version of the standard, it is stated that the calculation of the U-factor only takes place in instances where the manufacturer has not declared a value according to harmonized product standards (Danish Standard Association 2011). DS 418 shows a graph with U-factors for wood sashes and frames depending on the thickness of the sash or frame. Reference is made to EN ISO 10077-2 for a more detailed calculation of the U-factor for the sash/frame construction (2012a).

Moisture-Related Requirements

Together with the introduction of net-energy gain in 2010 in DBR, a requirement for the minimum acceptable surface temperature on the window frames was introduced for windows at replacement (9.3°C) (Danish Enterprise and Construction Authority 2010). For a calculation of the surface temperature, DBR10 refers to EN ISO 10077-2, although the standard only specifies the calculation of U-factors for the sash/frame construction and the linear-thermal transmittance for the spacer (2012a). But the surface temperature can at least be calculated when the U-factor is known.

Since 2008, DBR has stipulated that building structures and materials must not, on moving in, have a moisture content that is liable to increase the risk of mold growth (Danish Enterprise and Construction Authority 2008). This requirement minimizes the risk of moving into overly-damp buildings, both in new buildings and renovation projects and derives from the number of cases of mold growth in buildings in Denmark. The moisture content of a material that is in equilibrium at 75% rh is normally taken as the critical surface humidity regardless of surface quality, temperature, and duration of moisture load, as knowledge of the specific level of the critical moisture content for different materials is rather scarce (de Place Hansen 2012; Nevander and Elmarsson 2006; Sedlbauer 2001).

Then, when the indoor relative humidity based on knowledge about moisture production, air change, etc., is known in a specific case, it is possible to calculate the minimum inner-surface temperature to avoid critical situations, as described in the following section.

METHODS TO CALCULATE MINIMUM ACCEPTABLE SURFACE TEMPERATURE

A simplified and easily-accessible method for evaluation of temperature and moisture conditions in and around a building element is described in EN ISO 13788, Section 5 (2012b). Using this method, the risk of surface mold growth or surface condensation can be calculated. The method is described briefly in this section, followed by some examples in the next section.

For each month the following steps are to be followed:

1. Define the external air temperature;
2. Define the external humidity;
3. Define the internal temperature in accordance with national practice;
4. Calculate the internal relative humidity;
5. Calculate the minimum acceptable saturation humidity or vapor pressure;
6. Determine the minimum acceptable surface temperature, $\theta_{Si,min}$; and
7. Calculate the minimum temperature factor, $f_{Rsi,min}$ from the minimum acceptable surface temperature, the assumed internal temperature and external temperature.

Then it is possible to determine the month with the highest risk of mold growth or surface condensation, expressed by the highest required value of $f_{Rsi,min}$.

The standard describes different ways of calculating internal relative humidity (step 4) designing for avoidance of mold growth, based on internal humidity classes, a constant relative humidity, or a fixed or variable air-change rate and fixed moisture supply. The standard operates with 80% rh as the limit for mold growth unless more specific information is available. Another calculation based on constant external relative humidity (95% rh) and the mean annual minimum on a daily basis is to be used for design to prevent surface condensation on low thermal-inertia elements such as windows.

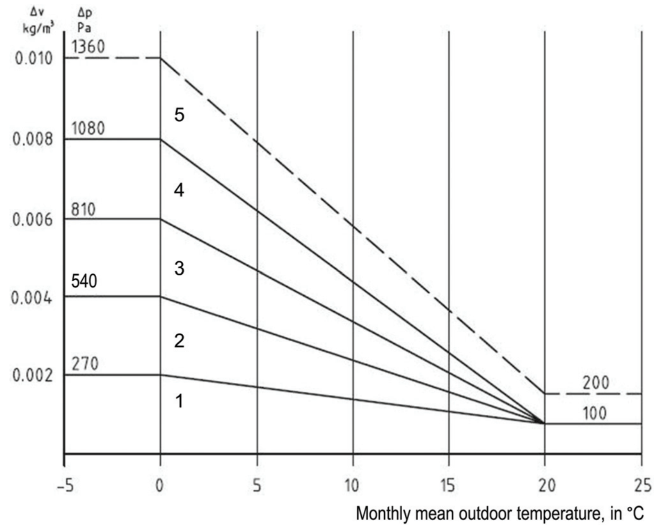

Figure 8 *Variation of internal humidity classes with external temperature. Maritime climates (Western Europe). Humidity class 1: unoccupied buildings, storage of dry goods, class 2: offices, dwellings with normal occupancy and ventilation, class 3: dwellings with unknown occupancy, class 4: sports halls, kitchens, canteens, and class 5: special buildings, e.g. laundry, brewery and swimming pool (ISO 2012b).*

Internal Humidity Classes

It is generally considered that the moisture supply or internal humidity load, i.e., the difference between moisture content (in g/m^3) in the indoor and the outdoor air tends to be relatively constant in a house in the colder part of the heating season (external temperature below 0°C), while it decreases with increasing external temperature due to increased ventilation. EN ISO 13788 defines five humidity classes to describe the internal humidity load for different types of buildings, based on data from buildings in Western Europe (maritime climates), see Figure 8 (2012b).

The placement of dwellings with normal occupancy in humidity class 2 is in accordance with findings reported in (Geving et al. 2008; Künzel 2006; Francisco and Rose 2010; Brandt 2013).

Fixed or Variable Air-Change Rate and Fixed Moisture Supply

Instead of using humidity classes, a constant internal relative humidity or a fixed or variable air-change rate (h^{-1}) and fixed moisture supply can be used. This is especially relevant in mechanically ventilated buildings. The DBR stipulates an air-change rate of 0.3 l/s/m^3 (equaling 0.5 h^{-1} in a building with a normal ceiling height of 2.5 m). The size of the moisture production should be set according to the use of the building and the number of people using it; in a single-family house with three or four people 7.0–9.5 kg per 24 hours is appropriate.

Constant External Humidity and Mean Annual Minimum Temperatures

The standard EN ISO 13788 also prescribes how to calculate the risk of surface condensation on a lightweight construction (2012b). In this case, the temperature shifts relatively fast and therefore the mean annual minimum temperature on a daily basis should be used as external temperature and 95% rh as external humidity.

EXAMPLES OF CALCULATION OF MINIMUM ACCEPTABLE SURFACE TEMPERATURE

A calculation based on internal humidity classes is made for the Danish Test Reference Year TRY (Andersen et al. 1982), with an internal humidity load corresponding with the upper limit of humidity class 3 and 75% rh as critical surface humidity for mold growth during the winter period (Brandt 2013). Table 6 shows that the highest value of the minimum temperature factor $f_{Rsi,min}$ is found in January. Comparing the corresponding minimum acceptable temperature $\theta_{si,min}$ with the inner-surface temperature of a window at a specific location, e.g., at the edge of the glazing, it can be evaluated whether there is a risk of mold growth.

Table 6. Calculation of the Minimum Acceptable Surface Temperature and the Minimum Temperature Factor According to EN ISO 13788 (2012b) for Buildings in Humidity Class 3 (Upper Limit) Based on TRY (Andersen et al. 1982) and 75% rh as Critical Moisture Level (Mold Growth), Internal Temperature: 20°C. (Brandt 2013)

Month	θ_e °C	φ_e	p_e Pa	Δp Pa	p_i Pa	$p_{sat}(\theta_{si})$ Pa	$\theta_{si,min}$ °C	$f_{Rsi,min}$
Jan	–0.6	0.94	546	810	1356	1808	15.9	0.802
Feb	–1.1	0.91	507	810	1317	1756	15.5	0.785
Mar	2.6	0.91	670	718	1388	1850	16.3	0.786
Apr	6.6	0.82	799	576	1375	1833	16.1	0.711
May	10.6	0.78	996	434	1430	1907	16.8	0.655
Jun	15.7	0.67	1194	253	1447	1929	16.9	0.289
Jul	16.4	0.74	1380	228	1607	2143	18.6	0.614
Aug	16.7	0.71	1349	217	1566	2088	18.2	0.453
Sep	13.7	0.85	1332	324	1656	2207	19,1	0.854
Oct	9.2	0.87	1012	483	1495	1994	17.5	0.765
Nov	5	0.91	793	633	1426	1901	16.7	0.781
Dec	1.6	0.88	603	753	1356	1808	15.9	0.778

Table 7. The Minimum Acceptable Surface Temperature Based on TRY (Andersen et al. 1982) at the Upper Limit of Different Internal Humidity Classes Calculated According to EN ISO 13788 (2012)

Critical RH	Minimum Acceptable Surface Temperature, $\theta_{si,min}$			
	Internal Humidity Class			
Φ_{si}	1	2	3	4
75% rh	8.2 °C	12.5 °C	15.9 °C	18.8 °C
100% rh	4.1 °C	8.2 °C	11.5 °C	14.3 °C

The example in Table 6 has been expanded in Table 7, which shows the minimum acceptable surface temperature for mold growth (75% rh) and surface condensation (100% rh), calculated for the upper limit of the different internal humidity classes shown in Figure 8. Table 7 is based on average monthly values from TRY (Andersen et al. 1982) for temperature (–0.6°C) and relative humidity (94% rh) for January, which is the critical month in Denmark regardless of humidity class. Internal temperature is 20°C.

Table 8 compares the level of the minimum acceptable surface temperature using internal humidity classes and the other preconditions according to EN ISO 13788 (2012b). For ‘internal humidity classes’, the upper limit of humidity class 3 is used as internal moisture load, like in Tables 6 and 7. For ‘fixed or variable air-change rate and fixed moisture supply’, the air-change rate is $0.25 + 0.04\ \theta_e\ h^{-1}$ and the moisture production is 0.4 kg per 24 hours, representing 4-5 persons. The chosen conditions are estimated to be comparable.

Table 8. Calculation of the Minimum Acceptable Surface Temperature Using Different Preconditions According to EN ISO 13788 (2012b). Climate Data for January in Denmark (Andersen et al. 1982), Internal Temperature: 20°C.

Method	Preconditions	$\theta_{si,min}$ 75% rh	$\theta_{si,min}$ 100% rh
Internal humidity classes	Upper limit class 3	15.9°C	11.5°C
Constant internal RH	50% rh	13.6°C	9.3°C
Fixed air-change rate and moisture production	$0.25 + 0.04\theta_e\ h^{-1}$, 0.4 kg/h	17.2°C	12.7°C
Fixed external rh	95% rh	16.6°C	12.2°C

In all four cases, results based on 75% rh (mold growth) and 100% rh (condensation) are shown, although the first three methods are aimed at mold growth and the last one at surface condensation. Only the results for January are shown, like in Table 7, as this is the critical month.

Apart from the case of constant internal RH, Table 8 shows that the different methods give comparable results and that 9.3°C used as critical surface temperature to prevent surface condensation in the DBR is too low. The results for a specific building will, of course, depend on the actual moisture conditions. Note that 9.3°C is based on 0°C as external temperature, while the results of the calculation based on internal humidity classes and fixed external RH in Table 8 are based on –0.6°C as external temperature, representing January. The temperature 9.3°C corresponds to 9.0°C at –0.6°C as external temperature.

DISCUSSION

Minimum Acceptable Surface Temperature—Based on a Daily Changing Temperature

In preparing the requirements for DBR10, the Technical University of Denmark recommended a value of 12°C to avoid surface condensation, which is comparable with the values for 100% rh in Table 8 (Laustsen and Svendsen 2008). Calculations based on the upper limit of humidity class 3 (ISO 2012b) as internal humidity load, 95% rh as external relative humidity, 20°C as internal temperature, and daily minimum external temperature based on the Danish DRY (Lund 2001) gave a temperature factor with a maximum value of 0.65 corresponding to 12.9°C as the minimum acceptable surface temperature. As this is an extreme situation that occurs just once a year, 12°C was recommended, corresponding to a temperature factor of 0.6.

EN ISO 13788 prescribes the use of a mean annual minimum temperature on a daily basis and 95% rh as external relative humidity, implying that only one single calculation is to be made, representing the whole year (2012b). By using daily minimum temperatures and calculating the temperature factor for each day, it is not only possible to calculate whether there is a risk of surface condensation in a specific case or not, but also the number of days when there is a risk. This makes it possible to compare different window solutions to see which of them gives the highest risk of surface condensation. However, in combination with the daily minimum temperature, Laustsen and Svendsen used 95% rh as external humidity (2008). It can be argued that such preconditions are overdone to be on the safe side, and thus exaggerating the risk of condensation of specific window solutions.

BYG DTU describes an even more detailed calculation of the risk of surface condensation using the external temperature in the heating season on a time basis, and also using a program to calculate the U-factor as a function of the external temperature with a fixed internal temperature and another program to calculate the inner-surface temperature as a function of the external temperature (2009a). The calculations show that the minimum temperature factor, f_{Rsi} is nondependent on an external (θ_e) and internal (θ_i) temperature between –10°C and 20°C. This means that it is possible to calculate the inner-surface temperature (θ_{si}) hour by hour by using a reference year for the external temperature:

$$\theta_{si} = \theta_i \cdot f_{Rsi} + (1 - f_{Rsi}) \cdot \theta_e \tag{2}$$

Minimum Acceptable Surface Temperature—Based on a Fixed Air-Change Rate

When the minimum acceptable surface temperature became a requirement in DBR10, the value was set at 9.3°C, but only at replacement of windows (Danish Enterprise and Construction Authority 2010). DBR10 also introduced the concept of moisture safety in relation to energy savings to highlight that care has to be taken when renovation or replacement is carried out to save energy. In some cases, renovation is not advisable, as it is not possible to renovate without a high risk of causing moisture-related problems.

Since 2003, the Association of Danish Window Manufacturers had recommended that windows should have an inner-surface temperature of at least 7°C (Association of Danish Window Manufacturers 2003) which was increased to 8.5°C in 2008 and 9.3°C in 2010. The Association argued that 12°C corresponds to 60% rh indoors, which is a very high level during winter, indicating that it represents a situation with insufficient ventilation (Association of Danish Window Manufacturers 2009). Figure 9 shows how the internal relative humidity changes over the year depending on the humidity class.

The Association suggested that calculations should be based on 0.5 h^{-1} as the fixed air-change rate, as required in DBR10 and a moisture production of 10l per 24 hours, representing 4–5 persons. This is in accordance with EN ISO 13788, which prescribes the use of humidity classes, a constant relative humidity or a known moisture supply and ventilation rate (2012b). In that case, an 80 m^2 house, which is very small for 4–5 persons, results in 9.3°C as the minimum inner-surface temperature, indicating that 9.3°C should be on the safe side.

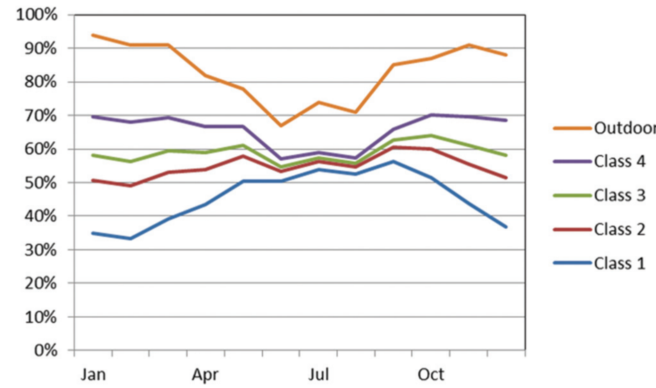

Figure 9 *Internal relative humidity in internal humidity classes 1–4 (upper limit) (simplified) and in external air during the year. Based on EN ISO 13788 (2012) and Danish Test Reference Year (TRY) (Andersen et al. 1982). Internal temperature 20°C, except June and September (22°C), and July and August (23°C).*

The U-factor of a window is calculated for the window as a whole, according to EN ISO 10077-1 (2006) and DS 418 (2011), which means that the inner-surface temperature is also calculated for the window as a whole. However, the lower spacer becomes 0.2°C–1.0°C colder than the rest of the window due to internal convection, which means that some kind of safety margin is necessary, which speaks for a higher value than 9.3°C to be used (BYG DTU 2001).

It can also be argued that the use of 0°C as external temperature is too high. The inner-surface temperature at the spacer is reduced from 8.2°C to 5.3°C for a window with wood sash/frame construction, double glazing, 15 mm distance between glazing panes and a traditional spacer made of aluminum if the external temperature is reduced from 0°C to –5°C (BYG DTU 2009a) resulting in moisture-related problems.

The risk of condensation is very dependent on the air-change rate and often people do not operate the fresh air valves correctly, closing them during winter to avoid a draft. A 50% reduction of the air-change rate can increase 50–100 times the number of hours per year with a risk of condensation (BYG DTU 2001), depending on the materials used for the sash/frame construction. Table 8 shows a case with a fixed moisture supply (0.4 kg/h) and a variable air-change rate (0.25 + 0.04 θ_e h^{-1}), resulting in 12.7°C as minimum acceptable surface temperature (surface condensation). With 0.5 h^{-1} as fixed air-change rate, the temperature becomes 6.5°C showing the effect of sufficient ventilation all year round.

Minimum Acceptable Surface Temperature vs. Amount of Ventilation

Problems with specific types of wood/aluminum windows, e.g., type B1 in Table 5 and a similar window with a 7.5°C inner-surface temperature, demonstrate that it was relevant to introduce the minimum acceptable surface temperature in the Danish building legislation concurrently with the U-factor or net-energy gain as a parameter for windows. It also demonstrates that the recommendation by the Danish window industry (7.0°C and later 8.5°C) was too low. The manufacturer of window B1 has since improved the construction by inserting a thermal interruption between the internal wood part and the external aluminum part (type B2) or by exchanging aluminum with a composite material (type B3). The inner-surface temperature for these solutions is 9.5°C and 10.3°C, respectively. They apply to the requirements in DBR10 and are markedly higher than 7.2°C, but they are still lower than 12°C as given by Table 8 and recommended by Laustsen and Svendsen (2008).

Other window manufacturers have improved their products as well, in some cases introducing materials with low-thermal conductivity such as GFRP (see Table 5), acknowledging that the thermal bridge at the edge construction becomes too big when using aluminum, which results in problems with surface condensation. This shows that the industry responds to new requirements. Since 2008, warm spacers made of stainless steel, polycarbonate, or a combination of stainless steel and polypropylene have in most cases been standard for new windows in Denmark and since 2010 for all new windows (Association of Danish Window Manufacturers 2013). In some cases, spacers of aluminum are still used at replacement. It remains to be seen how durable the warm spacers are compared with the traditional aluminum solution.

During the preparation of DBR10, introducing a requirement for the inner-surface temperature, the Danish window industry argued that internal climate problems should not only be solved by setting requirements to windows, but by focusing also on the importance of sufficient heating and ventilating (Association of Danish Window Manufacturers 2009). Sufficient heating becomes more important as radiators are replaced by floor heating.

Ensuring sufficient ventilation by opening the windows from time to time is also important, not least when the building is new and construction moisture needs to be removed or when the windows in an old building are replaced. However, in many cases surface condensation was detected, although the requirements for air change in the building regulations were followed obliging people to remove water from the inside of windows every morning. As buildings are becoming more air tight to reduce energy loss, this problem might increase.

On the other hand, DBR10 prescribes that new multi-family houses must have mechanical ventilation with heat recovery. This might ensure sufficient ventilation, as the building user will no longer experience cold air coming through fresh-air valves and therefore do not block them. Furthermore, the system does not rely on the occasional opening of windows. However, internal humidity may still be high if the internal moisture production is higher than foreseen in the humidity classes of EN ISO 13788 (2012). In the future, the problem might therefore increasingly be limited to single-family houses.

Level of Minimum Acceptable Surface Temperature—Political Considerations

By choosing 9.3°C as the minimum acceptable surface temperature, the Danish authorities were accused of listening too much to the window manufacturers and letting the consumers down, being aware that some windows with a sash/frame construction and thermal interruption on the market in 2009 were not able to meet a 12°C requirement recommended by (Laustsen and Svendsen 2008). If this is true, the minimum acceptable surface temperature is not only a matter of protecting the building user, but also a political question of protecting national interests. However, the authorities have had this problem before and solved it by indicating future requirements years before they became effective.

Concerning energy performance, DBR has, since 2006, included voluntary classes (low-energy classes). At present, low-energy classes indicate the minimum requirements for 2015 and 2020, leaving time for the industry and clients to develop and promote building components that comply with these voluntary classes. The introduction of net-energy gain and minimum acceptable surface temperature for windows instead of U-factor has had the same effect. As a result the implementation of warm spacers has led to a number of products that comply with what could be expected to be requirements in 2020. However, it remains to be seen how much the requirement for the minimum acceptable surface temperature will be raised. Other countries could learn from this experience as well. In 2015, the requirement for net-energy gain is expected to be tightened to –17 kWh/m^2 per year and the requirement for the minimum acceptable surface temperature is to be reconsidered.

How Different Internal Humidity Classes Can Be Taken into Account

The relationship between the minimum acceptable surface temperature at the upper limit of the different internal humidity classes and the acceptable relative humidity is shown in Figure 10, as an extension of the results in Table 7. Figure 10 shows that if the acceptable RH level increases, the acceptable minimum surface temperature decreases. For example, a building in humidity class 3: If 75% rh can be accepted at the inner surface, then the window should be designed to ensure an inner-surface temperature that is at least 16°C. However, if 85% rh can be accepted, 14°C is acceptable as inner-surface temperature.

From Figure 10 it can be seen that the present requirement for the inner-surface temperature (9.0°C, based on –0.6°C as external temperature) fits well with the upper limit for internal

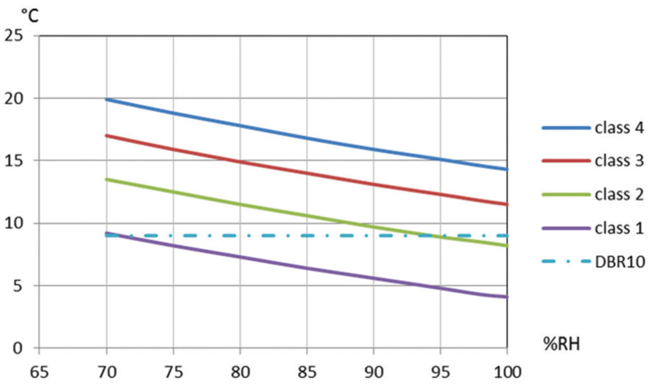

Figure 10 *Minimum acceptable inner surface temperature, $\theta_{si,min}$ depending on the acceptable RH at internal humidity classes 1, 2, 3, and 4 (upper limit). External air temperature and relative humidity based on the Danish Test Reference Year TRY (Andersen et al, 1982). DBR10: The present requirement for inner-surface temperature in the Danish Building Regulations (Danish Enterprise and Construction Authority 2010) adjusted to –0.6°C as external temperature.*

humidity class 2 representing dwellings with normal occupancy and ventilation. However, this indicates that dwellings with unknown occupancy, represented by internal humidity class 3, will have problems with surface condensation using windows with 9.0°C as inner-surface temperature, highlighting the need of raising the requirement.

Suitability of the Method

Depending on whether it is a question of evaluating the risk of surface condensation or mold growth for a specific window, or whether it is a question of comparing different designs of windows, it can be argued how detailed the calculations should be.

The calculation for the risk of mold growth according to EN ISO 13788 is a static calculation based on monthly mean values, not taking into account the daily variations and the heat capacity (2012b). The calculation of the risk of surface condensation is based on a single case where the external temperature is an average, taken over several years, of the lowest mean daily temperature of each year.

Another possibility is to make a calculation based on daily values for external temperatures and relative humidity. Or even data for each hour (BYG DTU 2009a). Then the number of days or hours where the acceptable surface temperature is lower than the inner-surface temperature for the window can be calculated. However, as long as the criteria for mold growth is not known in detail, i.e., for how many days or weeks the moisture conditions should be above a certain level to be critical, it is difficult to decide whether a day-to-day or month-to-month calculation is the more relevant.

Requirements Based on Risk of Surface Condensation or Mold Growth

The requirement of the inner-surface temperature in the DBR relates to the risk of surface condensation. As the examples in Tables 7 and 8 show, a requirement related to the risk of mold growth (75% or 80% rh) would become a problem for most of the windows available on the market today. However, most of the sash/frames of modern windows have some kind of surface treatment and are relative easy to clean. It is easy to see whether cleaning is necessary compared with a wall where mold growth can occur behind a closet or in other places that are difficult to access.

Condensation on windows is not only a question of good technical solutions in window design, but it is very much influenced by the moisture production and the airflow at the internal side of the window, i.e., height/width ratio of the window, how close the internal side of the window is to the internal side of the wall, whether there is a curtain, a radiator, and/or a window sill, etc.

Part of this can be influenced by the architect and engineer that designs the building, but the behavior of the user is decisive. The user controls internal temperature, moisture load (for instance plants in the window), ventilation (opening of windows), and use of curtains. Replacement of old windows with new, tight, energy-efficient windows does not necessarily solve the problem with surface condensation if behavior patterns do not change.

Simulations of condensation on single glazing based on typical variations in internal and external climate in Norway (given in Figure 11) show how different conditions can be and this explains why some people complain of moisture problems while others have no problems.

However, as the development of windows has shown, it is possible to design windows with an inner-surface temperature higher than 13.2°C, which is the minimum acceptable surface temperature using the upper limit of humidity class 2 as internal moisture load, (see Table 6) representing dwellings with normal occupancy and ventilation. Therefore, in cases where the air-change rate complies with the requirements in the DBR and the internal moisture load is as expected, it should not be accepted that drying the windows on a daily/regular basis is necessary to avoid mold growth. Of course, if the internal moisture load is high, it is reasonable to require that people air rooms more often as a precaution.

CONCLUSION

The introduction of a minimum acceptable surface temperature in the DBR has been an important driver for the development of new window solutions, especially for the design of the sealing system for window panes as this is the critical point in relation to surface condensation and mold growth. The requirement is not strict enough to get rid of surface condensation. It can be stricter without ruining the window market as a number of windows are developed with an

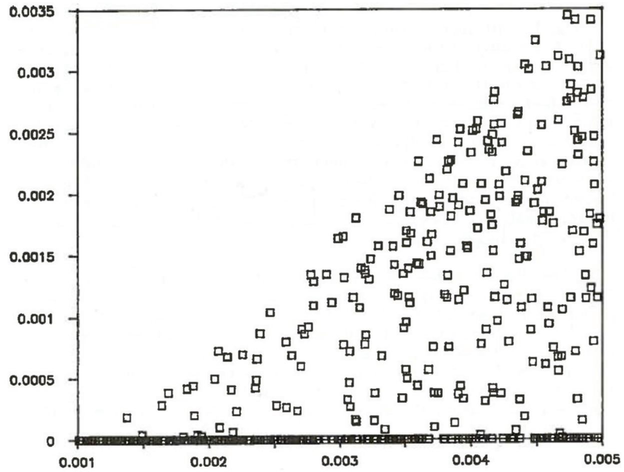

Figure 11 *Simulation of condensation on single glazing (500 cases). Difference in moisture concentration (kg/m³) between the surface and the indoor air (y-axis) versus extra moisture content (kg/m³) in the indoor air (Nielsen 1988). Values above zero on the y-axis are cases with condensation and cases with high values are cases with high condensation.*

inner-surface temperature high enough to avoid mold growth in dwellings with normal occupancy and ventilation.

Indications in the building legislation of the future requirements to the inner-surface temperature are recommended based on the experience from low-energy classes. Introduction of requirements in countries with similar problems is recommended as well.

More detailed calculations of the minimum acceptable surface temperature than described by the international standard are possible, but as long as the criteria for mold growth is not known in detail the present methods seems suitable.

Information on the minimum acceptable surface temperature gives the consumer a possibility to ask for this property for specific windows giving the opportunity to select between different windows. But the introduction of the minimum acceptable surface temperature does not stop complaints from consumers as this temperature is measured or calculated under specific conditions. It cannot take into account whether windows are mounted in the inner or outer part of the wall or the presence of curtains in front of the window during night. In both cases, the risk of surface condensation increases as the internal heat resistance is increased.

Increasing requirements for airtightness increases the importance of sufficient ventilation in order to avoid problems with condensation or mold growth, as the requirement for a minimum acceptable surface temperature in the building legislation is based on a certain internal humidity load.

NOMENCLATURE

E = energy

G = degree hours in the heating season based on 20°C as internal temperature

I = sunlight corrected for the variation of g value with angle of entry

U = thermal transmission coefficient

f = temperature factor

g = solar energy transmittance

p = water vapor pressure

θ = temperature

φ = relative humidity

Subscripts

e = external (outdoor)

i = internal (indoor)

ref = net-energy gain

si = internal surface

sat = saturation

w = window

REFERENCES

Andersen, B., S. Eidorff, L. Hallgreen, H. Lund, E. Pedersen, S. Rosenørn, and O. Valbjørn. 1982. Weather data for plumbing and energy. SBi Report 135, Danish Test Reference Year TRY (author's translation from Danish). Hørsholm: Danish Building Research Institute.

Applefield, D., C.S. Hansen, and S. Svendsen. 2010. Development of a slim window frame made of glass fibre reinforced polyester. *Energy and Buildings* 41(10):1918–25.

Association of Danish Window Manufacturers. 2003. T*echnical Conditions for DWV* (Danish Window Verification), 5th ed., addendum 3. (author's translation from Danish). Aarhus.

Association of Danish Window Manufacturers. 2009. Note to the Danish Enterprise and Construction Authority and the Danish Energy Agency (author's translation from Danish). Aarhus.

Association of Danish Window Manufacturers. 2013. Johny Jensen, personal communication with the author, January 21.

Brandt, E., ed. 2013. Moisture in buildings (author's translation from Danish). *SBi Directions 224*, 2nd ed. Copenhagen: Danish Building Research Institute.

BYG DTU. 2001. Energy properties of panes and windows—Part 11: Edge constructions with reduced thermal bridge, Report U-010 (author's translation from Danish). Lyngby: Technical University of Denmark www.vinduesvidensystem.dk/Kompendier/Kompendium11-vidensystem.pdf

BYG DTU. 2009a. Energy properties of panes and windows—Part 4: Development of energy efficient panes and windows, Report U-004 (author's translation from Danish). Lyngby: Technical University of Denmark www.vinduesvidensystem.dk/Kompendier/Kompendium4-vidensystem.pdf

BYG DTU. 2009b. Energy properties of panes and windows—Part 9: Overview of possibilities for developing better panes and windows, Report U-008 (author's translation from Danish). Lyngby: Technical University of Denmark. www.vinduesvidensystem.dk/Kompendier/Kompendium9-vidensystem.pdf

Danish Enterprise and Construction Authority. 2006. *Building Regulation 1995,* Addendum 12 to (author's translation from Danish). Copenhagen.

Danish Enterprise and Construction Authority. 2008. Building Regulations 2008. Copenhagen.

Danish Enterprise and Construction Authority. 2010. Building Regulations 2010. Copenhagen.

de Place Hansen, E.J., ed. 2012. Guidelines on building regulations 2010. *SBi Guidelines 230*, 2nd ed. Hørsholm: Danish Building Research Institute.

Danish Standard Association. 2011. DS 418, *Calculation of Heat Loss from Buildings*, 7th ed. Copenhagen: Danish Standard Association.

ISO. 2006. EN ISO 10077-1, *Thermal performance of Windows, Doors and Shutters—Calculation of Thermal Transmittance—Part 1: General*. Brussels: European Committee for Standardization.

ISO. 2012a. EN ISO 10077-2, *Thermal Performance of Windows, Doors and Shutters—Calculation of Thermal Transmittance—Part 2: Numerical Method for Frames.* Brussels: European Committee for Standardization.

ISO. 2012b. EN ISO 13788, *Hygrothermal Performance of Building Components and Building Elements—Internal Surface Temperature to Avoid Critical Surface Humidity and Interstitial Condensation—Calculation Methods.* Brussels: European Committee for Standardization.

Francisco, P.W., and W.B. Rose. 2010. Temperature and Humidity Measurements in 71 Homes Participating in an IAQ Improvement Program. *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XI*, Clearwater Beach, Florida Dec 5–9, 2010.

Geving, S., J. Holme, and J.A. Jenssen. 2008. Indoor air humidity in Norwegian houses, Report R-189. C. Rode, ed. *Proceedings of the 8th Symposium on Building Physics in the Nordic Countries*, Lyngby: Technical University of Denmark.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel. 2006. World Map of Köppen-Geiger Climate Classification Updated. *Meteorologische Zeitschrift* 15:259–63.

Kragh, J. and S. Svendsen. 2009. Development of new types of energy windows of composite materials. *Design Proposals for Profile Systems,* Report BYG DTU R-203, (author's translation from Danish). Lyngby: Technical University of Denmark. http://www.byg.dtu.dk/~/media/Institutter/Byg/publikationer/byg_rapporter/byg_r203.ashx

Künzel, H.M. 2006. *Indoor Air Humidity in Dwellings—Limits for the Assessment of Protection Against Moisture* (author's translation from German). Stuttgart: Fraunhofer Institut für Bauphysik.

Laustsen, J.B. and S. Svendsen. 2008. *Analysis of Energy Requirements for Windows in the Energy Labeling System and the Danish Building Regulations for 2010, 2015 and 2020,* Report BYG DTU SR-08-06 (author's translation from Danish). Lyngby: Technical University of Denmark. www.byg.dtu.dk/~/media/institutter/byg/publikationer/byg_rapporter/byg_sr0806.ashx

Lund, H. 2001. Design reference years and test reference years in Europe, Turkey and Israel, Electronic CIB Publication No. 262. Rotterdam: CIB General Secretariat.

Ministry of Housing. 1961. *Building Regulations for market towns and the country 1961* (author's translation from Danish). Copenhagen.

Ministry of Housing. 1966. Building Regulations for market towns and the country 1966 (author's translation from Danish). Copenhagen.

Nevander, L.E. and B. Elmarsson. 2006. Moisture handbook. *Practice and Theory* (author's translation from Swedish). Stockholm: Svensk Byggetjänst.

NFRC. 2010. Procedure for determining fenestration product condensation resistance values, NFRC 500-2010. Greenbelt, MD: National Fenestration Rating Council.

Nielsen, A. 1988. Prediction of risk for surface condensation. *Proceedings of Healthy Buildings*, *Volume 2: Planning, Physics, and Climate Technology for Healthier Buildings*, Stockholm: Sweeden, Swedish Council for Building Research, 325–333.

Nielsen, A. 1991. Analysis of heat loss and temperature conditions for spacers in sealed glazing, BYGGEFORSK Report O3411(author's translation from Norwegian). Trondheim: Norwegian Building Institute.

Persson, A., B. Jonsson, P.-O. Marklund, P. Wickman, and S.-O. Eriksson. 1994. Condensation on windows—causes, steps, dimensioning (author's translation from Swedish). *NUTEK Project 'Window now.*' Stockholm: Sweeden.

Sedlbauer, K. 2001. Prediction of Mould Fungus Formation on the Surface of and Inside Building Components. Stuttgart: Fraunhofer Institute for Building Physics.