Original Paper

Condensation on the outer surface of window glazings – Causes, effect on heat loss and method for prevention

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Fogging on the outside surfaces of window glazings increases if the thermal insulation of the glazing is improved, i.e., the k value is decreased as realized in the heat-insulating glasses currently on the market. The main reason for this is the radiation exchange with the open sky. The most endangered windows for fogging are the sky lights and glazings in the skin of buildings, e.g. structural glazing facades, because they are exposed to the largest portion of the open sky. The conditions of fogging are investigated and discussed, as well as its influence on the heat loss of glazings is demonstrated. By radiation exchange with the open sky, the heat loss of window glazings can be increased by more than a factor 2 in comparison to the standardized k value. However, fogging reduces heat losses in dependence on the outside air humidity. Fogging and heat loss can be considerably reduced by a low-emissive coating on the outer surface of glazings. The demands on such a coating are discussed. Also a method of double coating consisting of a low-emissive subcoating and a hydrophobic and anti-sticking top-coating is presented, which has a self-cleaning effect. Low-emissive and, at the same time, self-cleaning coatings, deposited on the outer surface of glazings are a new function of flat glass and may be a challenge to the glass industry in the next years.

Kondensation auf der Außenseite von Fensterverglasungen, ihre Ursache und Auswirkung auf den Wärmeverlust sowie ein Vorschlag zu ihrer Vermeidung

Kondensation von Luftfeuchtigkeit auf der Außenoberfläche von Fensterverglasungen häufen sich, wenn deren Wärmedämmung verbessert, d.h. ihr k-Wert abgesenkt wird, wie dies auf die heute vermarkteten Wärmeschutzgläser für Hochbauten zutrifft. Die wesentliche Ursache hierfür ist die Wärmeabstrahlung an den freien Himmel. Am gefährdetsten sind Dachfenster und Verglasungen in der Außenhaut von Gebäuden, z.B. Structural-Glazing-Fassaden, da sie einen großen Himmelsausschnitt sehen. Die Kondensationsbedingungen werden untersucht und diskutiert. Außerdem wird der Einfluß der Außenkondensation auf den Wärmeverlust der Verglasung aufgezeigt. Durch Wärmeabstrahlung an den freien Himmel kann sich der Wärmeverlust um mehr als einen Faktor 2 im Vergleich zum z.Z. genormten k-Wert erhöhen. Jedoch reduziert Außenkondensation den Wärmeverlust in Abhängigkeit von der relativen Luftfeuchtigkeit. Sowohl die Außenkondensation als auch die Wärmeverluste können durch eine niedrigemittierende Schicht auf der Außenoberfläche der Verglasung erheblich verringert werden. Die Anforderungen an eine solche Schicht werden aufgezeigt. Es wird auch ein Lösungsvorschlag in Form einer Doppelschicht gemacht, die aus einer niedrigemittierenden Unterschicht und einer hydrophoben Oberschicht besteht, auf der Schmutz nicht haftet. Mit einer solchen Schicht erhält das Flachglas eine weitere, neue Funktion und stellt damit eine Herausforderung für die Flachglasindustrie in den nächsten Jahren dar.

1. Introduction

Condensation of air humidity on outer window glazings, also termed fogging, is increasingly observed with improved thermal insulation of the glazings, i.e., the k value (often designated as U value in English literature) of the glazings has been reduced as realized at the standard heat-insulating glasses. Fogging on the outside surface of such glazings often gives cause for complaints because the clear transparency, the main benefit of window glazings, is spoilt [1 and 2].

In principle, the same effect can be observed on the outside of car glazings in the morning or in the night. At low temperatures, the fog changes into frost. The experience with cars is that fogging occurs if during the night or early in the morning the sky is cleared up and if the windows are positioned almost horizontally, i.e., sloping windows like windscreen glazings and rear windows are more and earlier fogged than the more vertically positioned side windows. This knowledge can be transferred to building glazings. Sky lights are more frequently fogged in comparison to wall windows.

Outside fog on insulating glass can easily be identified by moisture in the middle of the glazing and a moisture-free zone at its edges at the same time (figure 1). The opposite is true for the formation of fog on the room side of insulating glasses. The reason for this is the warmth bridge at the insulating glass edges.

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2. Conditions for fogging on outside surfaces

In order to explain condensation on outside surfaces of glazing, the conditions for condensation of air humidity have to be shown. Condensation on outer surfaces is al-

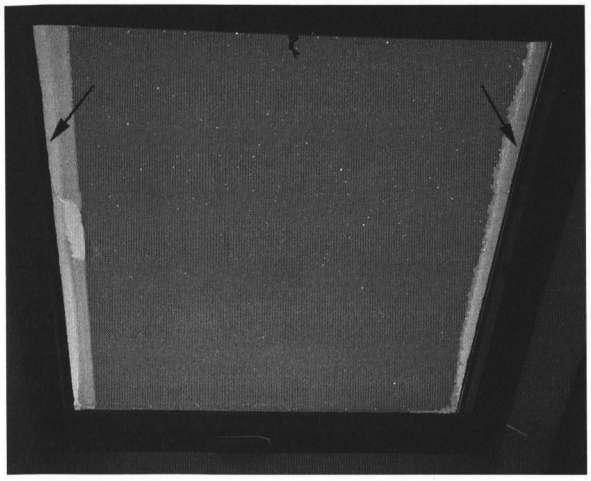


Figure 1. Outside fogging on a sky light with moisture-free zones (marked by arrows).

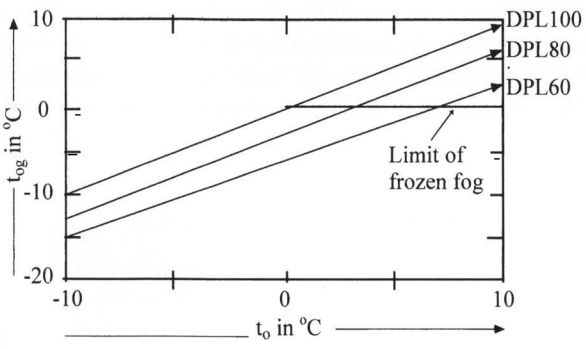


Figure 2. Condensation conditions for outside surfaces.

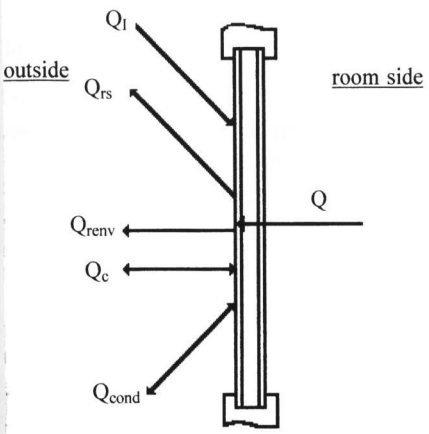


Figure 3. Heat flows from and to the outside surfaces of glazings.

ways observed if the surface temperature is lower than he dew point temperature, t_{dp}. The conditions for the outside condensation are therefore:

$$t_{og} \leq t_{dp} \leq t_o \,,$$

where t_{og} is the temperature of the outside surface of the glazing and t_o is the outside temperature. If

$$t_{og} \leq 0\,°C \,,$$

frost occurs.

The function $t_{og} \equiv t_{dp}(t_o)$ can be described in the outside temperature range $t_o = -10$ to $+10$°C studied in this work for the relative air humidity (RH) by straight lines (figure 2). These lines are termed in the following as "dew point lines" (DPL). Thus, DPL100, DPL80 or DPL60 are the straight lines for 100, 80 or 60% RH. Condensation occurs below DPL in dependency on the RH of the outside air.

3. Determination of the temperature on the outside surfaces

The question is why the temperature on the outside of the surface can fall below the outside air temperature, i.e., $t_{og} < t_o$, so that fog or frost occurs. According to DIN 4108 [3], fogging on the outer surfaces cannot happen.

The temperature behaviour of the outside surface can be determined by the heat flows from and to this surface (figure 3). The heat flows shown in this figure mean:

- at the outside
  - Q_{rs} = radiation exchange with the open sky,
  - Q_{renv} = radiation exchange with the environment, which has to be subdivided into exchange with the ground Q_{re}, with the covering of buildings in the vicinity Q_{rv}, and with the clouds Q_{rcl} [4], from which equation (1) is obtained:

$$Q_{renv} = Q_{re} + Q_{rv} + Q_{rcl} \,, \qquad (1)$$

  - Q_c = heat transfer by convection,
  - Q_{cond} = heat input in the case of water condensation according to the condensation heat (626 Wh/kg) or sublimation heat (719 Wh/kg) of water,
  - Q_I = heat input according to solar radiation;
- from the room side
  - Q = heat loss through the glazing.

Concerning these heat flows the following should be noted:

a) Q describes the real heat loss through the glazing from the room side. It follows:

$$Q \equiv k'(t_i - t_{og}),$$

where k' can be determined from the equation

$$1/k' = 1/k - 1/\alpha_o .$$

k is the k value of the glazing and α_o is the coefficient of heat transfer at the outside. According to DIN 4108 [3],

$$\alpha_o = 23\ \mathrm{W/(m^2\,K)} .$$

Because the value of $1/\alpha_o$ is small, it follows $k \approx k'$. In the following considerations the room temperature t_i is supposed to be 20 °C.

b) Q_I can be set to 0 because the formation of fogging is not observed in the case of heat input by solar radiation for which t_{og} exceeds t_{dp} and condensation can not occur. The often observed fog on the outer glass surface early in the morning exists because condensation from the night has not yet disappeared.

c) Q_{cond} is difficult to calculate. Therefore, the estimation of the limiting values of t_{og} influenced by Q_{cond} makes sense. Condensation or sublimation of water increases the surface temperature t_{og}. However, for reasons of limitation of vapour pressure in air, t_{og} cannot exceed the dew point temperature t_{dp}, i.e., $t_{og} \leqq t_{dp}$. Therefore, in the case of condensation, t_{og} must always fall below DPL for the corresponding outside humidity RH (see figure 2). They are the upper limit of condensation. The lower limit of t_{og} results from the assumption $Q_{cond} = 0$, i.e., if condensation does not occur. Therefore, the real temperature of the outside glass surface ($t_{og,real}$) falls between the calculated surface temperature t_{og} for $Q_{cond} = 0$ and the dew point temperature t_{dp}, i.e., it follows:

$$t_{og} \leqq t_{og,real} \leqq t_{dp} . \qquad (2)$$

Therefore, and because Q_{cond} is not the reason for condensation, in the following considerations Q_{cond} is set to 0 and the real outside temperature is estimated by equation (2).

d) Q_c is determined by the temperature difference $(t_{og} - t_o)$ as driving force. It follows $Q_c = \alpha_o(t_{og} - t_o)$. For the coefficient of the outside heat transfer α_o it follows: $\alpha_o = \alpha_c + \alpha_r$, where the first term describes the convective and the second one the radiative part of the outside heat transfer. As can be shown, convection can also not be the cause of fogging on the outer glass surface. But it can weaken or strengthen its formation. In the following, it is assumed that α_c may have the value 3.6 W/(m² K). This value follows for a wind velocity of 0.4 m/s, i.e., nearly calm, which favours condensation on the outside surface. (Note: In DIN 4108 the value for $\alpha_o = 23\ \mathrm{W/(m^2\,K)}$ results for a wind velocity of 4 m/s, which corresponds to strong wind.)

e) The term Q_{rs} can be determined by the Stefan-Boltzmann formula. If the sky is cloudless, the glazing is facing the troposphere which in moderate climate zones has temperatures down to −60 °C [5]. For the related equivalent black-body temperature t_s of the cloudless sky in such zones very different values are published in the literature [4]. In the following, it will be assumed that $t_s = t_o - 25$ °C, which may be a good approach. Because t_s is much lower than t_o, the heat flow by radiation to the cloudless sky is the main cause for the formation of condensation on the outside surface of window glazings.

f) The parts Q_{re}, Q_{rv}, and Q_{rcl} of the term Q_{renv} according to equation (1) can also be determined with the Stefan-Boltzmann formula. They can contribute to the fogging on the outer surface of glazings if the black-body temperature of the related objects is below the outside temperature t_o, too. That can be possible if the sky is cleared up. However, the determination of the black-body temperatures is also difficult. In the following, the assumption is made that the black-body temperatures t_{env} of all three objects are the same and $t_{env} = t_o - 3$ °C. In the literature [4], this assumption is made for the completely cloudy sky. But the temperatures of the two other objects do not differ essentially. This assumption simplifies the following considerations.

Because of the low heat capacity of the glazings and the big heat reservoir of the rooms behind the windows, nearly stationary conditions for the heat flows according to figure 3 can be supposed. With the above assumptions $Q_I = 0$, $Q_{cond} = 0$, and t_{env} is equal for all objects, it follows:

$$F_s(1 - F_{sh})\,(1 - F_{cl})\,Q_{rs} + (1 - F_s)\,(1 - F_{sh})\,(1 - F_{cl})\,Q_{renv} + Q_c + Q = 0 \qquad (3)$$

where

F_s = cut out rate of the sky which the glazing is facing,
F_{cl} = cloud-covered portion of the sky,
F_{sh} = shading rate of the glazing by the environment,
and with

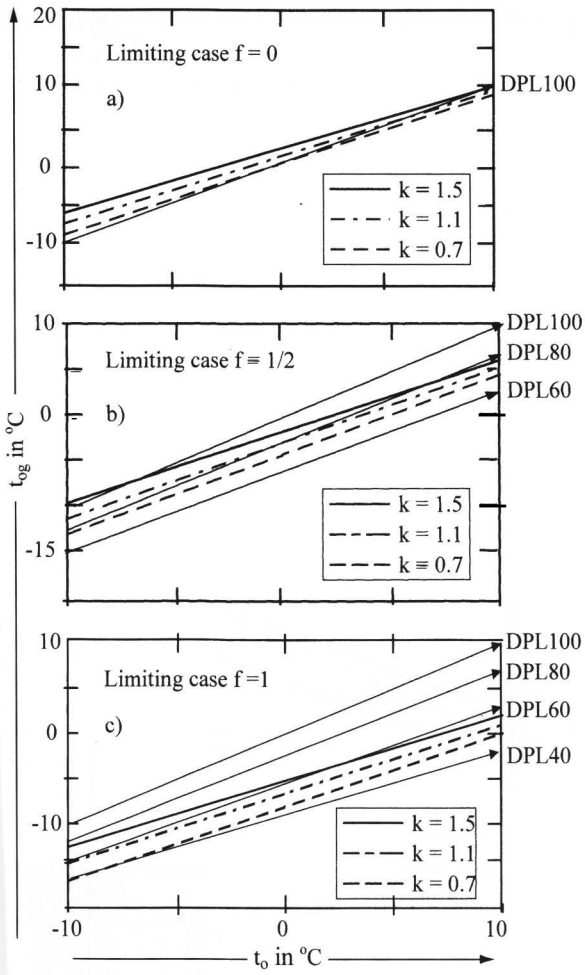
$$f = F_s(1 - F_{cl})\,(1 - F_{sh}) , \qquad (4$$

where f is the portion of open sky the glazing is exposed to [1], equation (4) can be written as follows

$$f\,Q_{rs} + (1 - f)\,Q_{renv} + Q_c + Q = 0 . \qquad (5$$

It makes sense to differentiate between the following three limiting cases.

- $f = 0$, corresponding to a completely cloudy sky ($F_{cl} = 1$) no matter what the positioning (F_s) and the shading (F_{sh}) of the glazing.
- $f = 1/2$, corresponding to a vertical positioning of the glazing ($F_s = 1/2$, the glazing is exposed to only half the hemisphere) without shading of the glazing ($F_{sh} = 0$) and with a cloudless sky ($F_{cl} = 0$).
- $f = 1$, corresponding to a horizontal (sloping) positioning of the glazing ($F_s = 1$) without shading ($F_{sh} = 0$) and with a cloudless sky ($F_{cl} = 0$).



Figures 4a to c. Behaviour of fogging on the outside surface of heat-insulating glasses with k = 1.5, 1.1 and 0.7 W/(m² K) according to [3] for the limiting cases a) f = 0, b) f = 1/2, c) f = 1.

Equation (5) solved to t_{og} shows in a good approach a linear dependency on the outside temperature t_o. Therefore, straight lines result for the outside temperature range (t_o = −10 to +10 °C), which in the following will be termed t_{og} lines. With these t_{og} lines, it can be determined in relation to the dew point lines (DPL) (see figure 2), whether condensation can occur or not. Condensation of outside air humidity on the outside of glazings occurs, if the t_{og} lines fall below a DPL corresponding to a certain air humidity RH.

It can easily be verified that with the above-stated conditions the entire formation of fog and frost on the outside surfaces of glazings falls between the t_{og} lines for f = 0 and f = 1, especially for vertically positioned windows between f = 0 and f = 1/2. (Note: If the building is situated on a high mountain with a view in a large plain, it follows f > 1/2. But this case may be exceptional.)

From the above explanations, it may be seen that the heat flows at the outside and thus, the real outside temperatures of glazings, can not be exactly determined. Therefore, it makes sense, as presented here, to determine the range of possibilities of fogging on the outside of glazings.

4. Fogging on glazings with $k \leq 1.5$ W/(m² K) according to [3]

Figures 4a to c show the t_{og} lines in the t_o range −10 to +10 °C for the limiting cases f = 0, 1/2, and 1 and for glazings with k = 1.5, 1.1, and 0.7 W/(m² K) according to DIN 4108 [3], which are these days on the market as heat-insulating glasses.

If f = 0 (figure 4a) the t_{og} lines for glazings with k = 1.5 and 1.1 W/(m² K) fall above DPL for 100 % RH (DPL100), i.e., for these glazings fogging can never occur on the outside surface. For the glazing with k = 0.7 W/(m² K), the t_{og} line falls below DPL100 for t_o > 0 °C, i.e., here fogging may be possible. However, the distance to 100 % RH is so small that fogging will not occur because there are hardly any climates with nearly 100 % RH and also other weakening influences for fogging come into play (see below). This is in accordance with the experiences hitherto gained with the heat-insulating glasses considered in this work. There is no outside fogging, if the sky is completely cloudy.

However, on glazings with a k value <0.5 W/(m² K) (e.g. glass sprandels) outside fogging can appear at t_o > 10 °C as the extrapolation of the results of figure 4a shows.

If f = 1/2 (figure 4b), RH values higher than about 70 % are critical for fogging. As can be seen, the probability of outside fogging increases with decreasing k values because the t_{og} lines shift to DPL with higher RH values. It can also be seen that the inclination of DPL is higher than that of the t_{og} lines, i.e., the probability of fogging increases with increasing outside temperatures t_o.

Both last results of figure 4b are in accordance with experiences. Complaints about outside fogging on glazings have been more frequent

- with decreasing k values, i.e., improved thermal insulation of glazings, and
- with high outside temperature t_o without direct solar radiation, e.g. early in the morning, in the night, and sometimes also in the late evening.

If f = 1 (figure 4c), for sloping installation of glazings, e.g. in sky lights outside fogging until down to about 50 % RH can be expected. With this positioning of glazings, the probability of outside fogging is very high and increases with decreasing (improving) k values and increasing outside temperatures t_o, as also pointed out for vertical positioning of glazings (see figure 4b).

A rough estimation shows that for same positioning of the glazing a k value decrease of 0.8 W/(m² K), which represents the range of k values of heat-insulating glass currently on the market, causes fogging at 14 % lower RH values, whereas the change from vertical to horizontal (sloping) positioning (f = 1/2 or 1) of the same

glazing (i.e. the same k value) causes fogging at about 20 % lower RH values. Therefore, one can conclude from figures 4a to c that the positioning of the glazing is more critical for fogging on the outside surface than the k value decrease, i.e., roof glazings have a higher fogging risk than vertical glazings in walls.

It must also be mentioned that shading, represented by the factor F_{sh} (see equation (4)), strongly influences the outside fogging of glazings. Thus, it has been observed that for glazings with the same k value positioned in the skin of a building, like e.g. with structural glazing or winter garden constructions, outside fogging is more frequent than on window glazings installed deep in the outside wall of buildings. The reason is that the heat radiation exchange, especially with the open sky, is shaded by this type of installation. This can be explained by calculations analogous to calculations of shading of solar energy input through windows in dependency on the positioning in the wall [6]. It could be proven that e.g. 25 % less solar energy falls into rooms if the windows are placed 20 cm deep in the outside wall. The results of such calculations can be transferred to the shading of heat radiation exchange. If all other conditions are equal, it follows: the deeper the windows are installed in the wall, the higher is the shading and consequently t_{og} of the glazing, and the lower is therefore the fogging probability of window glazings. The cloud-covered portion of the sky (F_{cl}) has the same function, however, is very difficult to number.

For the estimation of the probability of fogging, in figure 5 the range of possible outside temperatures of glazings t_{og} is depicted for the most critical insulating glass with the k value of 0.7 W/(m^2 K) in dependency on the limiting cases f = 0, 1/2, and 1 as considered in this work.

As stated above, the t_{og} lines for f = 0, 1/2 and 1 are limiting cases for fogging on outside glazings with respect to the above assumptions. The t_{og} line for f = 0 describes the upper limiting case and nearly corresponds with DPL100, i.e., no fogging occurs because of lacking radiation exchange with the sky. This case corresponds to the conditions as assumed in DIN 4108 [3]. Contrary to this, the t_{og} lines for the cases f = 1/2 and 1 correspond to the lower limiting cases, the worst cases, for which radiation exchange with the completely open sky occurs. The area between the t_{og} lines for f = 0 and f = 1/2 (hatched) represents the possibility of condensation (sublimation) of air humidity on the outside of vertically positioned window glazings, and the area between the t_{og} lines for f = 0 and f = 1 that for hozizontally (sloping) positioned ones. In dependency on the condensation, the cloud-covered portion of the sky (F_{cl}) the shading portion (F_{sh}), and the wind velocity (influencing α_c, see above), the outside temperatures of the glazings fall between these t_{og} lines. The DPL decide whether fogging occurs or not. The range of outside condensation possibilities depends on the k value of glazings.

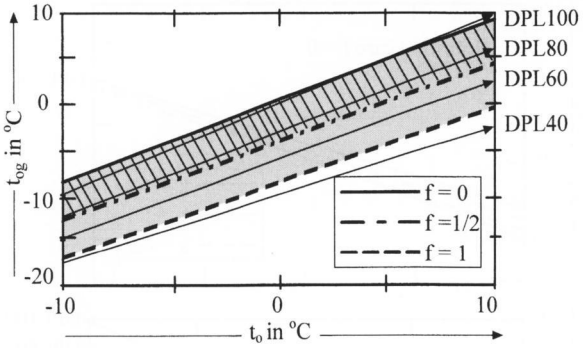
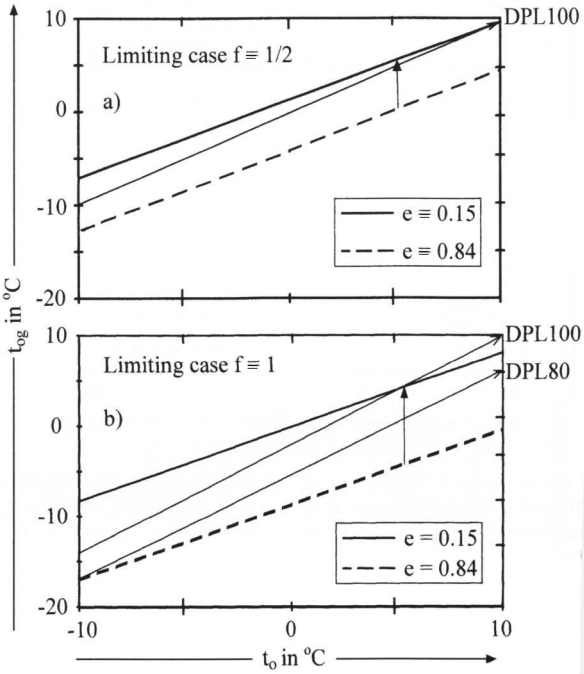


Figure 5. Range of fogging behaviour on the outside surface of heat-insulating glass with k = 0.7 W/(m^2 K) according to [3] for the limiting cases f = 1/2 and f = 1.



Figures 6a and b. Comparison of fogging behaviour of a heat insulating glass with k = 0.7 W/(m^2 K) according to [3] in cas the outside surface is uncoated (e = 0.84), respectively de posited with a low-emissive coating (e = 0.15) for the limitin cases a) f = 1/2, b) f = 1.

5. Influence of low-emissive coatings on the outside surface over fogging

Because radiation exchange with the sky is the mai reason for fogging on the outside surface of glazing there is the question whether a low-emissive coating ca act against fogging. As shown above, the most critic cases for fogging are the vertical and sloping positionin of the windows if the sky is cloudless and if there is n shading, i.e., if f = 1/2 and f = 1.

In figures 6a and b the t_{og} lines for f = 1/2 and 1 a compared for the most critical glazing with the k valu of 0.7 W/(m^2 K) for the case of uncoated outside surfac

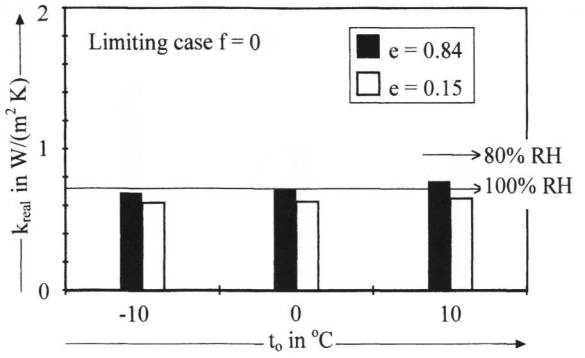


Figure 7. Comparison of the k_{real} values of a heat-insulating glass with $k = 0.7$ W/(m² K) according to [3] in case the outside surface is uncoated ($e = 0.84$, black beams), respectively deposited with a low-emissive coating ($e = 0.15$, white beams) for the limiting case $f = 0$.

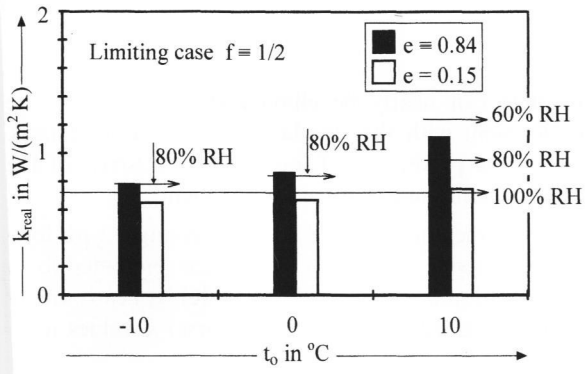


Figure 8. Comparison of the k_{real} values of a heat-insulating glass with $k = 0.7$ W/(m² K) according to [3] in case the outside surface is uncoated ($e = 0.84$, black beams), respectively deposited with a low-emissive coating ($e = 0.15$, white beams) for the limiting case $f = 1/2$.

f the glazing, i.e., with $e = 0.84$, respectively for a glazing with a low-emissive coating with $e = 0.15$. Today, such coatings on the base of SnO_2:F can be mass-produced on-line with the float glass process. These coatings are high-grade chemically and mechanically resistant.

A notable shift of the t_{og} lines in the direction to DPL100 can be stated if a low-emissive coating is deposited on the outside surface. For vertically positioned windows ($f = 1/2$, see figure 6a), it can be seen that fogging is not possible, because the corresponding t_{og} line falls above DPL100 for the whole t_o temperature range. For horizontally positioned (sloping) windows ($f \approx 1$, see figure 6b), the t_{og} line falls above DPL100 if ≤ 5 °C, i.e., fogging is not possible, either. For $t_o > 5$ °C, the t_{og} line falls between the lines DPL100 and DPL90, i.e., in this case fogging may be possible, but it is very improbable, because of weakening influences on fogging (see above). As can be verified easily, fogging is even more improbable for glazings with $k > 0.7$ W/(m² K) and a low-emissive coating on the outside. Therefore, figures 6a and b show that fogging on the outside of window glazings can be prevented by low-emissive coatings.

6. Influence of fogging on the outside surface of glazings on the heat loss of glazings

As seen in section 3., the heat loss from the room side through the glazing is described by the heat flow term

$$Q = k' (t_i - t_{og}) ,$$

i.e., like outside fogging, it depends on t_{og}.

In the building construction techniques, it is usual to standardize the heat losses of building elements in relation to the room side/outside temperature difference $(t_i - t_o)$. These as-standardized heat losses of a glazing are termed k_{real}. It follows:

$$k_{real} = \frac{Q_v}{t_i - t_o} = \frac{k' (t_i - t_{og})}{t_i - t_o} , \qquad (6)$$

i.e., k_{real} must depend on t_{og}, too. Therefore, heat losses through glazings and fogging conditions on the outside of glazings are correlated. For 100% RH t_{og} equals t_o. In this case, from equation (6) it follows $k_{real} = k' \approx k$ according to [3] (see also section 3.).

Figure 7 shows the comparison of the k_{real} values for the most critical heat insulating glass with a k value of 0.7 W/(m² K) and for $f = 0$ in the t_o temperature range −10 to +10 °C for the uncoated outside surface ($e = 0.84$), respectively for a low-emissive coating ($e = 0.15$). For the uncoated surface ($e = 0.84$, see black beams in figure 7), it can be seen that the k_{real} values increase with the outside temperatures t_o because of radiation exchange with the environment (assumption: $t_{env} = t_o - 3$ °C, see section 3.). For $t_o > 0$ °C, they exceed the k_{real} value for 100% RH and therefore, the k value according to DIN 4108 by up to 10%. That the k_{real} value at $t_o = -10$ °C falls below the line for 100% RH follows because of the assumption of $\alpha_c = 3.6$ W/(m² K) (nearly calm) in the present calculations instead of $\alpha_c = 18$ W/(m² K) (strong wind), as supposed in DIN 4108.

The k_{real} values for the glazing with a low-emissive coating on the outside surface are presented by the white beams in figure 7. The difference between the black and white beams shows the reduction in heat loss for this type of glazing. At $t_o = +10$ °C, the k_{real} value is reduced by about 16% in comparison to the uncoated glazing. The reduction in heat loss is exclusively due to the reduction in heat exchange with the environment.

In figure 8 the k_{real} values of the same glazings as in figure 7 are compared, but now for $f = 1/2$. In this figure the black beams show the k_{real} values for the uncoated outside surface ($e = 0.84$) without fogging. Here, one can see the influence of the t_{og} decrease due to radiation

exchange with the open sky (see also figure 4b). Subsequently, the k_{real} values increase again with increasing outside temperature t_o, as also seen in figure 7 for the heat exchange with the environment. However, in this case the k_{real} value for 100% RH (equal to the k value according to DIN 4108 [3]) is exceeded in the whole t_o range studied, i.e., in parallel to the probability of condensation the heat loss increases with increasing outside temperature t_o. At $t_o = +10\,°C$, the k_{real} value exceeds the k value by about 60%.

With fogging on the outside of the glazing, t_{og} increases due to the input of the condensation or sublimation heat of water. This results in a reduction of heat loss corresponding to the outside RH value. Subsequently, the k_{real} values fall between those without fogging (see black beams) and those relating to $t_{og} = t_{dp}$ according to the corresponding RH value (see arrows).

The result is:

- with fogging the heat losses are smaller than without fogging,
- however, with fogging they exceed the k value according to DIN 4108 (at 100% RH).

With low-emissive outside surfaces ($e = 0.15$, see white beams in figure 8), the k_{real} values also increase with increasing outside temperatures t_o due to the rest heat exchange Q_{rs} with the sky. The highest value is found again for $t_o = +10\,°C$. However, this increase results only to 7% in comparison to the k value according to [3]. An influence of heat loss due to fogging is practically excluded because condensation does not occur (see figure 6a).

Figure 9 depicts the k_{real} values of the same glazing as shown in figure 7, but now for $f = 1$. It can be seen that without fogging for the case of the uncoated outside surface $e = 0.84$ (see the black beams in figure 9), the heat losses increase considerably with increasing outside temperature t_o. The reason is the considerable t_{og} decrease because of the heat exchange with the open sky (see also figure 4c). The increase of k_{real} results in a nearly 110% higher k_{real} value at $t_o = +10\,°C$ in comparison to the k value according to DIN 4108. With fogging on the outside surface, the heat losses are again reduced according to the corresponding RH value (see arrows) for reasons discussed in figure 8.

With low-emissive coating on the outside surface ($e = 0.15$, see the white beams in figure 9), the heat losses are again considerably reduced according to the t_{og} increase (see also figure 6b). In this case, at $t_o = +10\,°C$ the k_{real} value exceeds the k value only by approximately 23%. In the case of fogging the k_{real} values would assume the values for the uncoated outside surface of glazings with fogging according to the corresponding RH (see arrows), because a water film tarnishes the low-emissive coating and has nearly the same emissivity as the original glass surface.

By further decreasing the emissivity ($e < 0.15$), the heat losses by heat exchange with the open sky can be more reduced. Eventually, heat losses by radiation

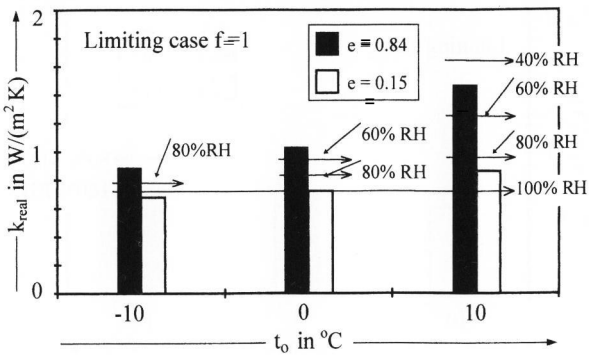


Figure 9. Comparison of the k_{real} values of a heat-insulating glass with $k = 0.7\,W/(m^2\,K)$ according to [3] in case the outside surface is uncoated ($e = 0.84$, black beams), respectively deposited with a low-emissive coating ($e = 0.15$, white beams) for the limiting case $f = 1$.

exchange can nearly be eliminated analogous to the development with the standard heat-insulating glasses. But for the prevention of fogging an emissivity of the outside coating of about 0.15 is sufficient.

The percentage of the k_{real} value changes with low-emissive outside coating, in this section presented for a glazing with a k value of $0.7\,W/(m^2\,K)$, is nearly transferrable to glazings with higher (worse) k values (e.g. $k = 1.1$ or $1.5\,W/(m^2\,K)$).

7. Method of a low-emissive coating on outside surfaces of glazings

The idea of preventing fogging on outside surfaces o glazings by a low-emissive coating is not new [7]. A mentioned above, semiconductor coatings on the base o SnO_2:F (e.g., K-glass of the Pilkington Group or EK(of the Saint-Gobain Group) are deposited on mass production scale on-line with the float glass proces These coatings are sufficiently mechanically and chem cally resistant for outside applications. However, it mus be proven whether the low emissivity of these coating is preserved if pollutions of the environment are de posited on it.

As seen above, water films by fogging are exclude with a low-emissive outside coating of $e = 0.15$ on th glazings. Wetting by rain is also no problem because i this case condensation is not possible and the heat loss not essentially increased (see figure 7, difference betwee black and white beams). The question is: What is th influence of the deposition of dirt by dust or dryin residues? Thick dirt films tarnish the low emissivity c coatings. Therefore, it should be investigated how the d position of dirt films on the outside surface of glazin can be avoided. Nature gives a hint with the self-cleanin

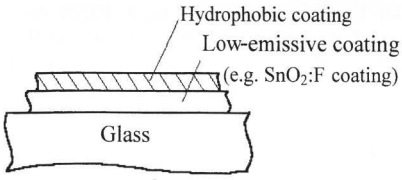


Figure 10. Proposal for a low-emissive, hydrophobic and anti-sticking coating on outside glass surfaces.

Lotus petal [8]. In any case, the low emissivity of coatings alone does not solve the problem. The solution may be a double coating, as presented in figure 10.

The subcoating may be the above-described semiconductor coating (SnO_2:F). The top coating has to fulfill the following requirements: It must be water-repellent (hydrophobic), anti-sticking for dirt, and transmissive in the far infrared, so that the low emissivity of the coating is not increased. Coatings which fulfill the anti-sticking and hydrophobic requirements have been developed in the past, e.g. on the base of fluoroalkyl silane (FAS) deposited with wet processes or plasma-enhanced chemical vapour deposition (PECVD) [9 to 11] or on the base of diamond-like carbon (DLC) coatings deposited also with PECVD [12]. But for the positioning on the outside surface of glazings these top coatings have to perform sufficient long-term stability, especially against solar degradation. It has to be proven whether the above-mentioned top coatings fulfill these requirements.

Another problem are the increased aesthetic requirements, especially the colour uniformity in the outside reflection of the SnO_2:F coating. But this should concern wall windows rather than sky lights.

8. Summary and outlook

Heat radiation exchange with the open sky in the night, i.e., without solar radiation, essentially influences the outside temperature of glazings t_{og}. This is the main reason why t_{og} can fall below the outside temperature t_o and why fogging may occur. (Note: According to DIN 4108 fogging cannot occur in principle.) Furthermore, t_{og} and therefore fogging is influenced essentially by the positioning of the window (F_s), the shading of the glazing (F_{sh}), and the cloud-covered portion of the sky (F_{cl}).

The t_{og} decrease by heat radiation exchange with the open sky influences the heat loss of window glazings, too. This heat loss can exceed the k value according to DIN 4108 [3] by nearly 110%. The reason is that in [3] the heat loss by radiation exchange due to the open sky is not considered. However, the heat losses are reduced by outside fogging of the glazings due to the input of the condensation (626 Wh/kg) or sublimation (719 Wh/kg) heat of water. The degree of reduction depends on RH.

Employing a low-emissive coating on the outside surface of glazings the heat radiation exchange with the whole outside area (e.g. sky, clouds, ground, environment) can be reduced, or possibly eliminated. By this means, not only the formation of fog or frost can be avoided on the outside of glazings, but also the heat losses from the rooms through the glazings can be considerably reduced.

With such a low-emissive coating, the heat losses of glazings become nearly independent of the climate zone in which a building is situated because only the heat losses by convection at the outside of glazings remain. This is essential for "zero-energy-houses" or "passive-energy-houses" [13] being developed at present. Furthermore, elimination of heat radiation would considerably simplify and improve the thermal balance calculations of buildings.

Low-emissive coatings on the base of semiconductor coatings, e.g. SnO_2:F, which can be mass-produced nowadays in conjunction with the float glass manufacturing are sufficiently mechanically and chemically resistant for the positioning on the outside surface of insulating glasses. But, this alone is not sufficient. Because the coating is in contact with the outside atmosphere, it can be soiled. Hereby, the low emissivity of the coating is tarnished. Therefore, the further main requirements for such a coating are: anti-sticking and water-repellent (hydrophobic) properties. The solution may be a double coating with the above-mentioned SnO_2:F layer as subcoating and a top coating which must have a high transmission in the far infrared and also guarantees the two other requirements. Such a top coating with sufficient long-term stability has to be developed.

The benefits of the proposed low-emissive outside coating for window glazings are:

- prevention of outside fogging,
- considerable heat loss reduction,
- self-cleaning effect of the glass surface.

Such a coating is a new function of flat glass and, according to the author, will be a challenge to the flat glass industry for the next years.

9. Nomenclature

e	emissivity of the outside surface
F_{cl}	cloud-covered portion of the sky
F_s	cut out rate of the sky
F_{sh}	shading rate
f	rate of the open sky
k	thermal transmittance of glazings according to [3]
k_{real}	k value according to the real heat loss
k'	k_{real} value for $t_{og} = t_o$
Q	heat loss of buildings from glazings
Q_c	heat transfer by convection
Q_{cond}	heat input according to water condensation or sublimation
Q_I	heat input according to solar radiation
Q_{rcl}	radiation exchange with the clouds
Q_{rc}	radiation exchange with the earth
Q_{renv}	radiation exchange with the environment
Q_{rs}	radiation exchange with the open sky

Q_{rv}	radiation exchange with the covering of buildings in the vicinity
RH	relative air humidity
t_{dp}	dew point temperature
t_{env}	black-body temperature of the environment
t_i	inside temperature
t_o	outside temperature
t_{og}	outside temperature of glazings
t_s	black-body temperature of the open sky
α_c	coefficient of outside heat transfer by convection
α_o	coefficient of outside heat transfer
α_r	coefficient of outside heat transfer by radiation

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