VIG - Vacuum Insulation Glass

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1 Introduction

In modern well insulated buildings U-values for walls of 0.3 W/(m^{2}K) or even below can be realized. In such buildings, glazings with typical U-values of 1.0 W/(m^{2}K) or higher are thermal weak spots in the façade. One attractive possibility to essentially improve the insulation properties of a glazing is to evacuate the space between the glass panes. This virtually eliminates heat transport due to conduction and convection of the filling gas. The glass panes can be prevented from collapsing by using a matrix of spacers (see Figure 1). Evacuated glazings are already available as a commercial product [NSG 2005], [QHI 2004], however have U-values of 1.1 W/(m^{2}K) or higher.

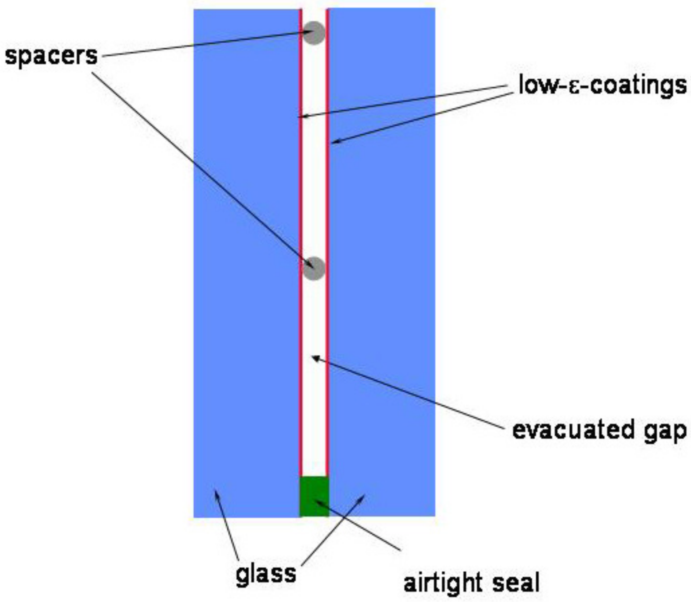

Figure 1: Principle of a Vacuum Insulation Glass construction.

Sponsored by the BMWA (German Federal Ministry of Economics and Labour, Berlin) within the project “VIG - Vacuum Insulation Glass”, a consortium of partners from industry and research institutes was established to investigate the feasibility of producing a vacuum insulation glazing with outstanding thermal properties. The goal is a U-value of 0.4 W/(m^{2}K). To achieve this, a production process for the airtight edge seal is being developed which avoids high temperatures in the low-ε-coated areas. Three methods are currently under investigation: glass-glass-joints, soldering metal foils, and high barrier adhesives. Such processes will allow the use of highly efficient low-emissivity-coatings to reduce thermal radiation, which otherwise is the major heat transfer mechanism in such an evacuated glazing.

2 Thermal concept

In a vacuum insulation glazing two glass panes, connected by an airtight edge seal, are evacuated to a pressure of below 10^{-3} mbar. The panes, each coated with a highly infrared-reflecting layer to minimize thermal radiation, are supported by a matrix of spacers to prevent collapse. In such an assembly four distinct heat transfer mechanisms contribute to the total heat transmission coefficient Λ_{tot} of the glazing: thermal conduction through residual gas (Λ_{gas}), spacers (Λ_{spac}), and edge seal (Λ_{seal}), as well as radiation heat transfer between the two panes (Λ_{rad}). In this paper, we use the heat transmission coefficient Λ, since it differs only slightly from the U-value for values of 0.5 W/(m^{2}K) or lower. The U-value also comprises the heat transition due to convection and radiation from the surfaces of the glazing to the ambient. The advantage of using the heat transmission coefficients is that Λ_{tot} can be approximated by simple addition of the individual heat transmission coefficients, negating coupling effects:

$$\Lambda_{tot} = \Lambda_{gas} + \Lambda_{spac} + \Lambda_{seal} + \Lambda_{rad}.$$

Each of the four heat transfer mechanisms will be discussed in the following sections.

2.1 Thermal conduction through residual gas

The thermal conductivity of gases between two panes can be significantly lowered by decreasing the pressure so that the mean free path length of the gas molecules equals or exceeds the gap width. The functional dependence of Λ_{gas} from gas pressure at 20°C and a gap width of 1 mm is shown in Figure 2.

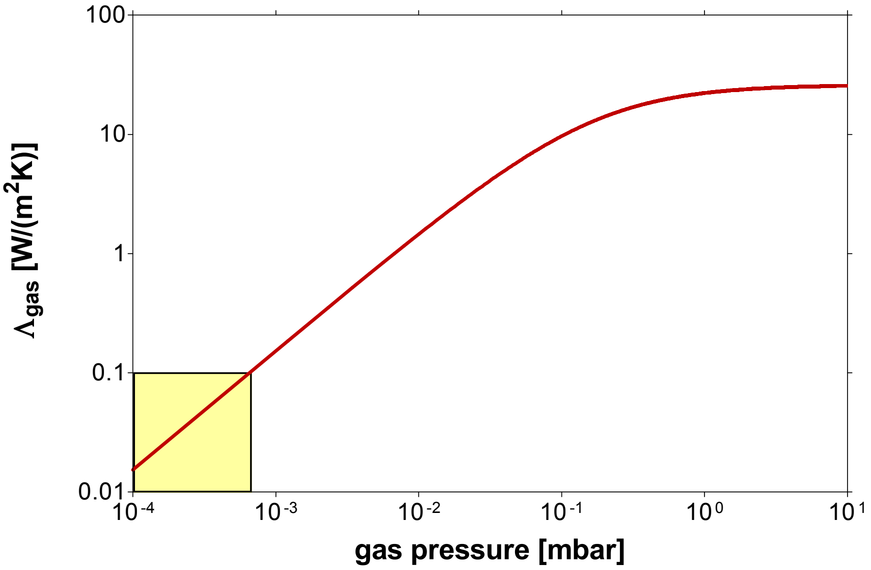

Figure 2: Calculated heat transmission coefficient Λ_{gas} as a function of gas pressure for a 1 mm air gap in a double log plot. For the low pressure region Λ_{gas} is proportional to the pressure.

To realize a heat transmission coefficient of $\Lambda_{gas} \leq 0.1$ W/(m^{2}K), the gas pressure in the glazing has to be lower than 10^{-3} mbar, and this not only at the time of fabrication but over a physical life of 20 years.

2.2 Thermal conduction through spacers

The spacers, which are necessary to prevent collapse of the panes due to ambient pressure, present thermal bridges that need to be minimized. Critical spacer parameters are the thermal conductivity of the spacer material, their shape and size, and the number of spacers per area. The influence of these parameters on the heat transmission coefficient Λ_{spac} is depicted in Figure 3.

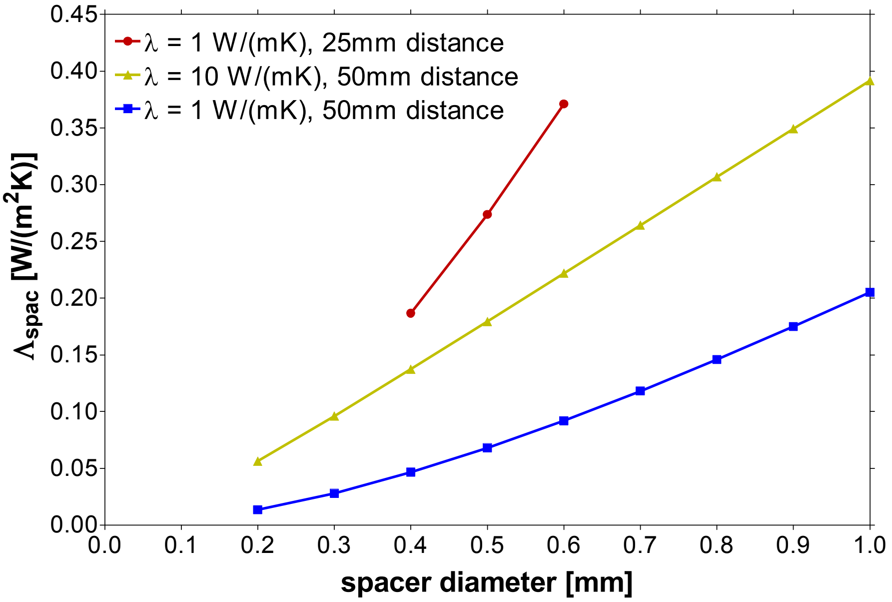

Figure 3: Calculated heat transmission coefficient Λ_{spac} for cylindrically shaped spacers as a function of spacer diameter with thermal conductivity and distance between two spacers as parameters.

Since the spacers are also responsible for the mechanical stability of the glazing, there has to be a compromise between thermal (small spacers with large distances) and mechanical optimization (big spacers with small distances). [Asano 2003] and [Griffiths 1998] report typical values for spacer distances in evacuated glazing between 20 mm and 40 mm. These values, however, depend on glass thickness. In the above mentioned studies, glass thickness is usually 3 mm to 4 mm. In a rectangular slab supported around the edge, an increase in pressure area by a factor of 4 can be compensated by an increase in material thickness by a factor of 2 [Netz 1983]. Transfused to the evacuated glazing, a spacer distance of 50 mm instead of 25 mm will result in approximately the same stress, if a glass thickness of 6 mm instead of 3 mm is used. With this concept, a heat transmission coefficient of Λ_{spac} = 0.07 W/(m^{2}K) for spacers of diameter 0.5 mm can be accomplished.

2.3 Thermal conduction through edge seal

A critical component of an evacuated glazing is the edge seal. It has to maintain the vacuum inside the glazing and to avoid mechanical breakage it has to compensate the generally different thermal expansion of the glass panes. Additionally, it has to be optimized from thermal point of view. Figure 4 shows the heat transmission coefficient Λ_{seal} for different kinds of sealing material and various edge seal widths. Since Λ_{seal} depends on the ratio of edge seal area to glazing area, all calculations were performed for a glazing of 1 m x 1 m. The curves represent two kinds of edge seal constructions, one with an edge seal that combines mechanical and vacuum requirements (lower insert in Figure 4) from glass or metal, and the other with two separate units, a spacer from glass or plastic for the mechanical stability and an additional metal foil on the edge for impermeability (upper insert in Figure 4). The data show that Λ_{seal} decreases with smaller seal widths, but nevertheless all values exceed 0.35 W/(m^{2}K) regardless of construction type. This means, that the heat flow through the edge seal alone is almost enough to cause the targeted U-value of 0.4 W/(m^{2}K). To avoid this, a highly insulating frame overlapping the edge seal can be used. The effect of such a frame is shown in Figure 5. For the calculations, the frame was assumed to be an ideal thermal insulator. With a frame overlap of 25 mm, Λ_{seal} can be decreased to a value of about 0.2 W/(m^{2}K) for all constructions. This result shows the necessity of highly insulating frame constructions, not only for such types of evacuated glazing, but for other highly insulating systems with thermal edge bridges, like Vacuum Insulation Panels (VIP), as well. The development of highly insulating frame constructions should therefore be a primary focus of research in the field of energy efficient building construction.

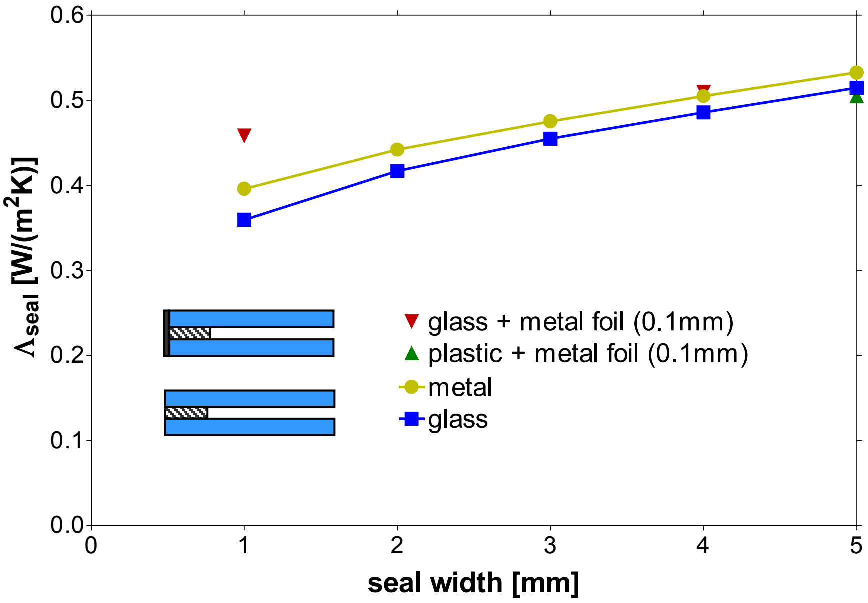

Figure 4: Calculated heat transmission coefficient Λ_{seal} as a function of the width of the edge seal, with the sealing material as parameter.

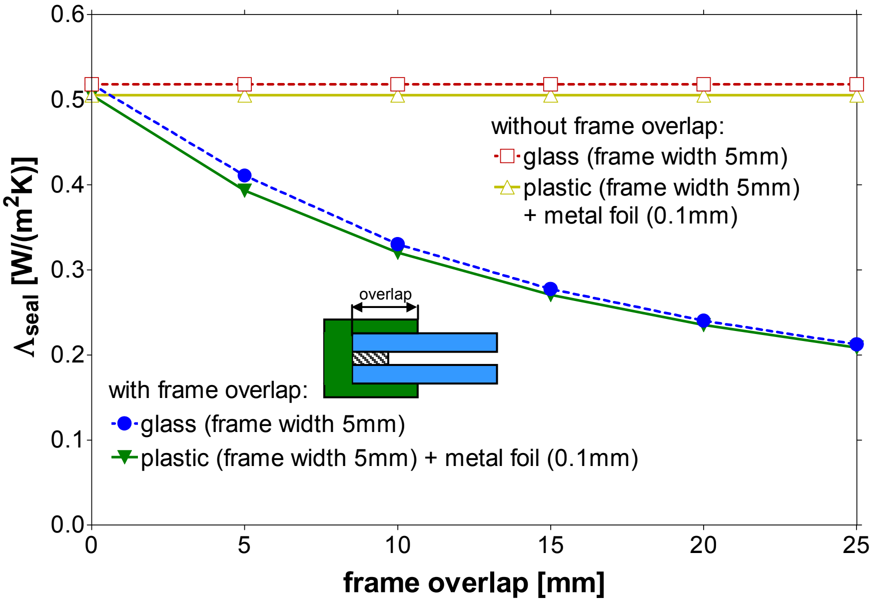

Figure 5: Calculated heat transmission coefficient Λ_{seal} as a function of frame overlap.

2.4 Thermal radiation between the two glass panes

Another important heat transfer mechanism is thermal radiative transfer between the two glass panes. In fact, this mechanism is the main reason for the relative high U-values of 1.0 W/(m^{2}K) or more of commercially available evacuated glazings [NSG 2005], [QHI 2004] and [Spiridonov 2005]. Since all these glazings use solder glass as edge seal material, temperatures of 400°C or more are necessary for the production process. Thus only temperature resistant low-emissivity-coatings (hardcoatings) with emissivities of about 0.2 or higher are usable. A low-temperature production process would allow the use of more efficient softcoatings with emissivities of 0.04 or even lower. The effect of emissivity on heat transmission coefficient is shown in Figure 6.

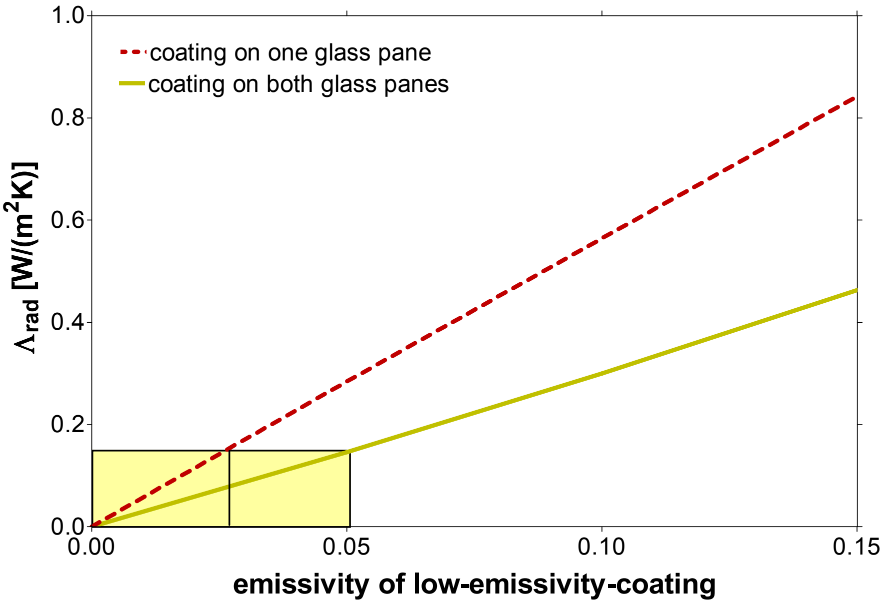

Figure 6: Calculated heat transmission coefficient Λ_{rad} as a function of surface emissivity.

If we allow a maximum heat transmission coefficient of Λ_{rad} = 0.15 W/(m^{2}K), the emissivity of the low-emissivity-coating has to be 0.03 for a single coating and 0.05 for coatings on both glass panes. Coatings with such values are commercially available, but it must be assured, that the production process of the evacuated glazing will not degrade the coating.

2.5 Overall heat transfer

As a first approximation for the calculation of the total heat transmission coefficient, which closely resembles the U-value for the whole glazing, the individual heat transmission coefficients can be added up. An overview of the range of heat transmission coefficients and the resulting U-values is shown in Table 1:

Table 1: Calculated heat transmission coefficients for the individual heat transfer mechanisms and the resulting total heat transmission coefficients and U-values of the glazing (gap width 1 mm). The ranges given represent variations in construction.

Λ_{gas}	0.02-0.1 W/(m^{2}K)
Λ_{spac}	0.07-0.4 W/(m^{2}K)
Λ_{seal}	0.2-0.5 W/(m^{2}K)
Λ_{rad}	0.15-0.9 W/(m^{2}K)
$\Lambda_{tot} = \Lambda_{gas} + \Lambda_{spac} + \Lambda_{seal} + \Lambda_{rad}$	0.44-1.9 W/(m^{2}K)
U-value	**0.41-1.4 W/(m^{2}K)**

It is of critical importance to suppress the thermal radiative transport and to install such an evacuated glazing within a highly insulating frame, if the desired low U-values are to be achieved. Especially the reduction of thermal radiation transport by use of highly efficient low-emissivity-coatings requires a low-temperature process for the edge seal construction.

3 Edge seal concept

As was shown in paragraph 2, the gas pressure within the glazing must be kept below 10^{-3} mbar. This sets very severe conditions to the tightness of the edge seal and requires leakage rates of $\leq 10^{-12}$ mbar•l/s. Possible sealing materials currently available include glass and metal foils; other materials, such as high barrier coatings based on inorganic-organic polymers (ORMOCER®), are currently under development [Amberg 2003]. All three types of material are investigated in the project and are outlined in the following sections.

3.1 Glass-glass joints

In commercial evacuated glazing solder glass is used as edge seal material. However, present construction methods heat up the whole glazing to about 400°C to melt the solder glass and form the edge seal. One way to avoid such high temperatures all over the glazing is to inject the heat directly into the solder glass with a laser beam. First experiments showed promising results with a special solder glass prepared with additives to give a high absorption in the wavelength range of the laser. A functional glass-glass connection could be produced that was free of cracks and had sufficient mechanical strength. The next step will be to investigate the resulting temperature distribution across the glass panes and to optimize the process to decrease the temperatures in a wide section of the panes to below 200°C, which would permit the use of highly efficient low-emissivity-coatings.

3.2 Soldering metal foils

A second approach is the use of metal foils as barrier. This method is widely used in opaque vacuum insulation panels (VIP), where laminates with thin films of aluminium or PE-coated Al-foils as barrier material are state of the art. In contrast to VIPs, where the foils cover the whole panel, the transparency of a vacuum insulation glass restricts their application area to the edge of the glazing. This requires a tight connection between glass and foil.

In first experiments to produce such a connection, metal foils were soldered directly to a glass surface. However, due to the differing thermal expansion coefficients of glass and metal, the results were not satisfying. A second step involved the use of a thin intermediary layer of solder glass between metal and glass surface, with the thermal expansion coefficient of the solder glass in-between that of metal and glass. This improved the connection considerably and resulted in joints with sufficient strength, but the required leak tightness could not be achieved up to now, due to small cracks. A heat treatment of the glass before and after the soldering process will be tested in a next step. Adhesives as joint material are also under investigation.

3.3 High barrier adhesives

An alternative to the soldering of glass or metal foils is the use of high barrier adhesives. The high mechanical strength of such adhesive joints has been proven in increasing numbers of façade applications, where glass-glass or glass-metal joints were realized. Various companies produce such adhesives that are already used in low-pressure applications. These products may be further optimized to fulfil the stringent tightness requirements needed in a vacuum glazing edge seal. In addition, new high barrier materials on the basis of inorganic-organic polymers are currently under development. [Amberg 2003]. Besides, there are hybrid polymer layer systems which feature good adhesion to glass and metal surfaces. [Kron 2001], [Kron 2004]. By combining barrier and adhesive properties the further development towards barrier adhesives should be feasible. This is why hybrid polymer materials, too, seem to be potential candidates for this application.

The two big advantages of adhesives is their processability at temperatures below 200°C, combined with a certain flexibility compared to soldered glass-glass or glass-metal joints. This second property favours the compensation of thermal stress within the edge seal due to high temperature gradients of the glazing. At the moment, the permeation rates of the tested adhesives lie above the tolerable values by a factor of 100. However, there is potential of improvement.

4 Conclusions

There are evacuated glazings commercially available with U-values of 1.1 $W/(m^2K)$ or higher. This relative high U-value is due to a high-temperature production process that prevents the use of effective low-emissivity-coatings, like softcoatings. Calculations show, that a U-value of 0.4 $W/(m^2K)$ is possible for an evacuated glazing of 1 m^2 under the following conditions:

- thermal radiation heat transfer is suppressed by a low-emissivity-coating with an emissivity of 0.03 on one pane, or an emissivity of 0.05 on both panes,
- the glazing is set in a highly insulating frame with an overlap of 25 mm on the edge seal,
- the pressure within the glazing is $\leq 10^{-4}$ mbar, and
- the spacers are thermally optimized and set at a distance of 50 mm.

Three methods are under investigation to produce a low-temperature edge seal: glass-glass-joints, soldering metal foils, and high barrier adhesives. At the current state of research, the use of high barrier adhesives seems the most promising method. However, problems have to be solved regarding barrier properties and outgasing behavior of the adhesives. Vacuum insulation glazing with U-values of 0.4 $W/(m^2K)$ will be highly promising for building and automotive applications. Further information can be found on the website of this project: www.vig-info.de.

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