A PARAMETRIC STUDY OF A METAL SANDWICH VIP

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VIPs in Practice - Industry Needs and Case Studies

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ABSTRACT

The superior insulation performance of vacuum insulation makes it an attractive alternative when adequate insulation performance is to be achieved without adding too much to the thickness of a construction. A conventional vacuum insulation panel consists of a porous core and a surrounding gas-tight envelope. The envelope, often consisting of a polymer or a composite polymer foil, is often vulnerable to mechanical strain, however. Our efforts have been focused on the development a vacuum insulation panel of the more robust kind, consisting of metal plates connected with thin foil at the edges. The panel is to be produced at atmospheric conditions, later to be vacuumed through a valve.

This study is concerned with minimising the thermal loss at the edges of the panel. The investigations include a parametric survey of the effects of thermal conductivities, shapes and thicknesses of the covering metal plates and the metal foil at the junction. The calculations have been carried out using the finite element method. It is shown how a robust outer plate can be applied with a negligible effect on the thermal loss at the edges. Furthermore the effects of constructing a serpentine edge are compared to the effects of extending the length of the joint in the direction of flow.

1. INTRODUCTION

Vacuum insulation panels and sandwiches offer the thermal insulation of traditional materials with the thickness differing by a factor of 5 to 10. Among the vast possibilities provided by the slenderness of VIP panels are floor and ceiling constructions, terrace insulation, sandwich elements and prefabricated façade elements (Binz, 2005).

The research at the dept. of Building Technology at the Royal Institute of Technology in Stockholm, KTH, is currently focused on the possibilities of applying vacuum insulated panels or sandwiches as a part of a prefabricated building system. Of particular interest are the possibilities to apply robust vacuum insulation panels in precast concrete. This study is focused on the effects of various parameters on the thermal heat loss at the junction between the faces of the vacuumed envelope.

The economic consequences of applying VIPs are important to the feasibility of making that choice. One might for instance compare the costs of trading VIPs with traditional insulation and the gain in income through increase of rentable space through a more slender construction.

Assuming a modified interest rate in the range of 0,03 - 0,07 and a period (lifetime) of 50 years the net cost per square meter outer wall per year, C_{net}, has been calculated* for Swedish conditions and is shown in figure 1 below.

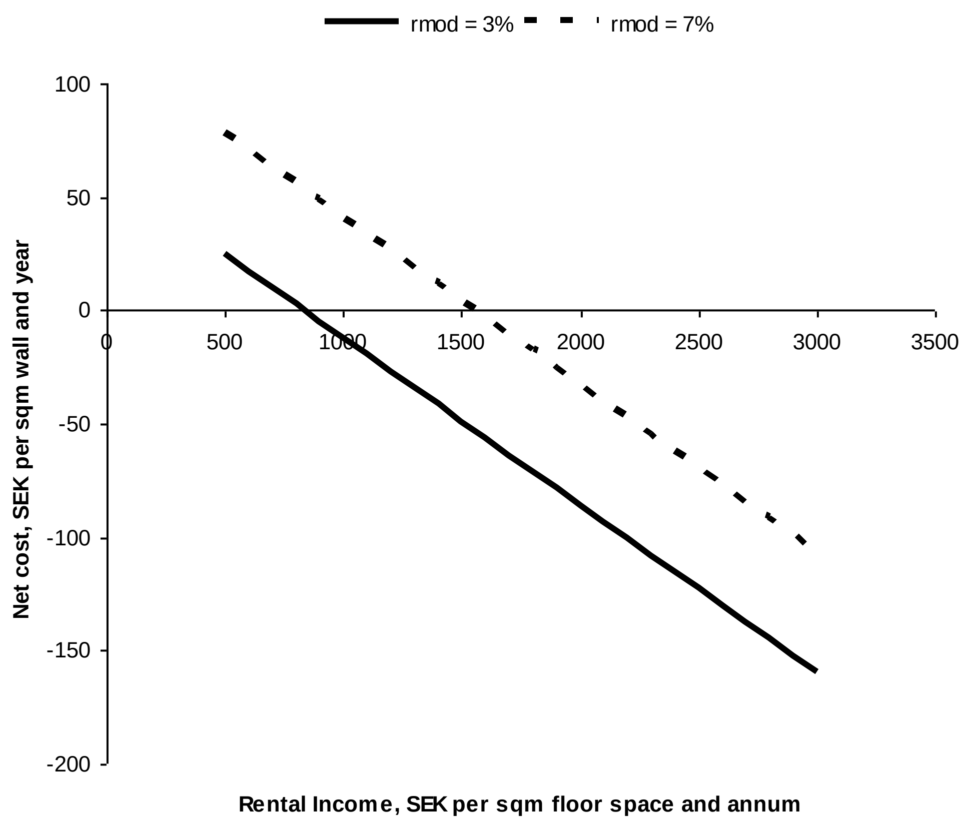

Figure 1. Annual net cost of applying VIPs as a function of rental income.

The calculations are based on a panel size of 600 by 1000 mm^2 and a thickness of 30 mm at a cost of about 1090 SEK per panel, which should be well within the range of many of the VIP products available today (Pramsten and Hedlund, 2009). The center of core thermal conductivity is assumed to be 0,004 $Wm^{-1}K^{-1}$ that with a thermal edge loss of 0,01 $Wm^{-1}K^{-1}$ gives a net U-value of about 0,187 $Wm^{-2}K^{-1}$. The cost of traditional insulation with a thermal conductivity of 0,04 $Wm^{-1}K^{-1}$ is assumed to be 1000 $SEKm^{-3}$. For an average annual rental income of 1000 SEK per square meter one can also calculate the net cost of applying VIPs as a function of the cost of the vacuum insulation panels. Applying the same prerequisites as before we obtain that a 50% reduction in the prize will quadruple the net gain of applying VIPs, assuming a average annual rental income of 1000 SEK per square meter.

A vacuum insulation panel is essentially a panel, consisting of a fine porous core and an enclosing envelope, from which the air has been evacuated.

Conduction through the solid matrix of the core is limited by using materials with geometric structures that minimize the area of contact between the particles while the radiative heat exchange between the interior surfaces of the core material is determined by the temperatures as well as the geometries and surface properties, the latter which can be improved by the use of additives.

The combination of pore size and low pressure prevents thermal transport through convection of the gases of the core. Conduction through the collision of gas molecules is eliminated by using core material with pore size less than the mean free path of the gas molecules, which in turn depends on the extent of evacuation. Consequently the gas pressure that has to be obtained within the envelope in order to reach a certain value of thermal conductivity in the VIPs depends on the pore structure of the material applied in the core. Fumed silica, for instance, maintains a constant thermal conductivity of about 0,004 $Wm^{-1}K^{-1}$ up to a gas pressure of about 10 mbar, the value being the double for a tenfold pressure of 100 mbar. Material with coarser pores, however, such as polyurethane, polystyrene or fiber glass will only maintain a comparable constant level up to a pressure just above 0,1 mbar with a fourfold thermal conductivity at a pressure of 10 mbar (Fricke et al, 2006; vip-bau.de,2009).

A leakage of the envelope will therefore cause the thermal conductivity to increase with time, a problem that to a certain level can be dealt with by surpassing the minimum required level of vacuum, providing a margin of decline. The rise of internal pressure and the accumulation of moisture are, however, the main threats to the long term thermal performance and service life of VIPs (Simmler and Brunner, 2005).

High barrier laminates, consisting of several layers of Al-coated polyethylene and polyethylene terephthalate, have provided the possibilities of VIPs with a lifetime of 50 years but with the kernel limited to a porous material like fumed silica or better in terms of pore size (Fricke et. al, 2006). Coarser core materials will, on the other hand, require all metal envelopes, such as stainless steel (vip-bau.de, 2009; Thorsell, 2006).

Other factors that may affect the choice of envelope are, for instance, the threat posed by damage during installation and the risk of degradation due to humidity, alkaline environment and the exposure to UV-radiation (Simmler and Brunner, 2005; IEA Annex 39).

The thermal properties are, however, not only determined by the properties of the core but also by the thermal losses that occur where the VIPs meet, i.e. The thermal loss at an edge is often described by the linear thermal transmittance coefficient, ψ, $Wm^{-1}K^{-1}$ that relates to the total heat flow as described by the following equation

$$\Phi_{tot} = U \cdot A \cdot \Delta T + \psi \cdot l \cdot \Delta T \text{ W} \quad (1)$$

Where

Φ_{tot} = total flow, W

U = heat transfer coefficient, $Wm^{-2}K^{-1}$

ΔT = temperature difference across the component

ψ = linear thermal transmittance coefficient, $Wm^{-1}K^{-1}$

l = length of thermal bridge, m

Several studies have been carried out on the thermal bridges associated with VIPs. Tenpierik and Cauberg presented analytical models for calculating this thermal edge effect for thin high barrier laminates around VIPs (Tenpierik and Cauberg, 2007) while Thorsell and Källebrink studied the effects of applying a serpentine edge on a metal panel (Thorsell and Källebrink, 2005).

Other researchers have investigated the different thermal bridges that arise when VIPs are applied in different constructions and various building details (Schwab et al., 2005; Ghazi Wakili et al, 2005; Nussbaumer et al, 2006, Platzer, 2007).

2. PARAMETRIC STUDY

The aim of the parametric study is to provide input for the design of a robust vacuum insulation panel. The choice of materials will ultimately be restrained by the environment, in which the panel will be placed, but it is of interest to study how the thermal conductivity of the cover and the edge will affect the thermal loss at the edges. Applying a thicker, more robust, cover will not only protect the panel (sandwich) but can also enable the use of a core material with coarser pores. The effects of cover thickness are therefore also studied. Another way of protecting the panel is to apply a layer of insulation adjacent to the cover. The thermal edge loss is therefore calculated for a 20 mm thick layer with different thermal conductivities, λ_{outer}. Finally it is investigated how the length of the edge affects the thermal bridge.

The two dimensional steady state calculations were carried out with the FEMLAB Multiphysics 3.5 finite element program. The total flow across the segment is obtained through boundary integration. Using equation (1) the thermal edge loss is evaluated by comparison with the calculated flow for a segment with a thermal resistance corresponding to center of core.

Based on the literature the thermal conductivity of the core material, λ_{core}, is assumed to be $4 \cdot 10^{-3}$ $Wm^{-1}K^{-1}$, which is the value for fumed silica (Simmler and Brunner, 2005). The calculations below are based on thermal conductivities of the cover in the ranges from 20-200 $Wm^{-1}K^{-1}$ which roughly emraces the range of values for stainless steel, steel and aluminum.

The geometry and boundary conditions are shown in figure 2. The outermost boundaries of the model are assumed to have a heat transfer coefficient of 25 $Wm^{-2}K^{-1}$ and an ambient temperature of 0˚C for all instances while the heat flux towards the interior is determined by a heat flux of 8 $Wm^{-2}K^{-1}$ and a surrounding temperature of 20˚C. No heat transfer is assumed to occur across the vertical boundaries of the model.

The core has a thickness, d_{core}, of 20 mm while the thickness of the cover, t_{cover} and the joints, t_{joints} are 0,05 mm. The width of the model was determined by raising it beyond influence on the outcome of the calculations.

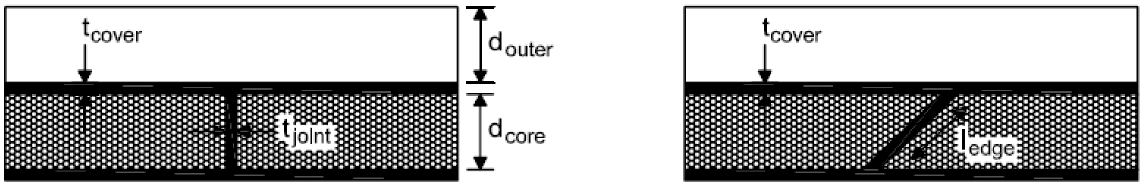

Figure 2. The geometry of the calculation model. The picture on the right shows the elongated edge. The outer layer was only applied in one series of simulations.

3. RESULTS

The study included more than 120 simulations. The following diagrams provide a representative extract of the results obtained. Figure 3 below illustrates the influence of the thermal conductivity of the cover of the envelope.

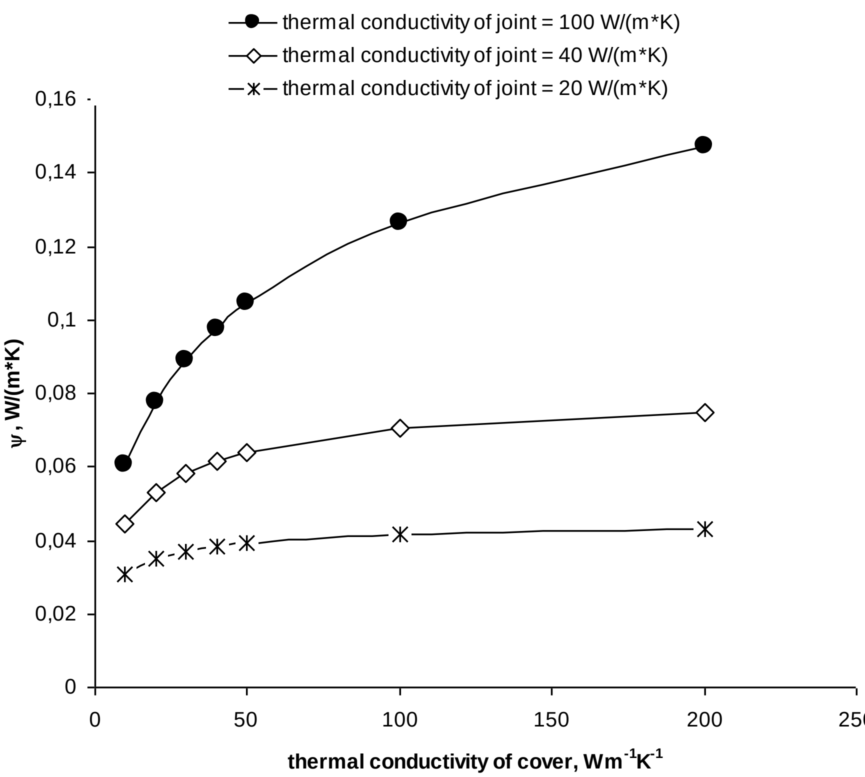

Figure 3. The influence of the thermal conductivity of the cover on the linear thermal loss at the joint, ψ.

Figure 3 shows that a cover with a high thermal conductivity may give a drastic increase in thermal loss at the edges. It does also illustrate that this effect is substantially reduced with a joint having a relatively low thermal conductivity. With a thermal conductivity of the edge at 20 $Wm^{-1}K^{-1}$ the thermal bridge increases moderately from about 0,03 to 0,04 $Wm^{-1}K^{-1}$ as the lambda value of the cover goes from 10 to 200 $Wm^{-1}K^{-1}$. For an edge with a thermal conductivity of 100 $Wm^{-1}K^{-1}$, on the other hand, the increase is more than twofold, from 0,06 to more than 0,14 $Wm^{-1}K^{-1}$.

The effect of making the cover of the envelope thicker is shown in figure 4. The effect of cover thickness is clear and increases with an increase in thermal conductivity, but is marginal for low lambda values.

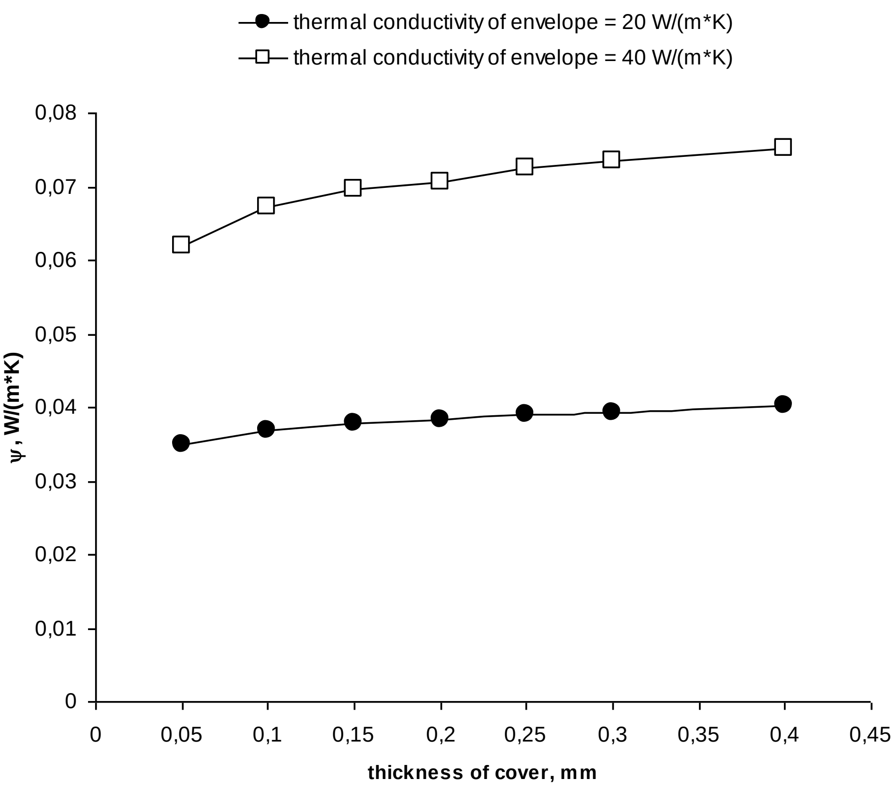

Figure 4. The influence of the cover thickness on the linear thermal loss at the joint, ψ.

The effects of placing a 20 mm layer of insulation outside the envelope are strong as shown in figure 5. As expected the thermal bridges are negligible with an outer insulation with thermal conductivity on pair with that of the core. The effect of this outer layer is also clearly of significance, however, for lambda values close to those for traditional insulation, the thermal bridge being reduced by more than one third of its' value when an outer layer with a lambda value of 0,15 $W/m^{-1}K^{-1}$ is replaced with a layer of 0,04 $W/m^{-1}K^{-1}$.

The results seem to be in line what those of Ghazi Wakili et al (Ghazi Wakili et al, 2005) that studied the effects of staggered layers as well as embedded panels.

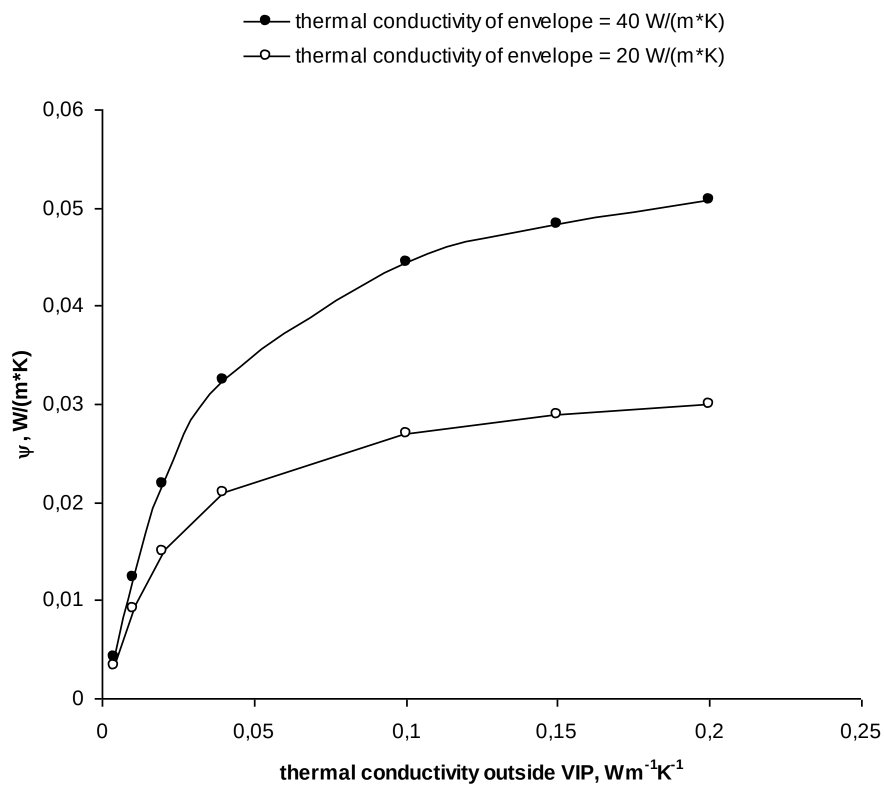

Figure 5. The linear thermal loss at the joint, ψ with an adjacent insulation of 20mm.

Figure 6 shows the results that were obtained when the edge length, l_e, was increased. The gains are obvious. Other things being equal, the doubling of the edge length will about halve the effect of the thermal bridge.

The results may be compared with those of Thorsell and Källebrink that investigated the use of a serpentine edge as the means to deal with the large thermal bridge that arises when using metals sheets as the envelope (Thorsell and Källebrink, 2005). The panels in question had a core with a thermal conductivity of 0,005 $W/m^{-1}K^{-1}$ while the heat conductivity of the stainless steel of the envelope was assumed to be 15 $W/m^{-1}K^{-1}$. Using numerical calculations the authors calculated the total heat flow through the constructions, while the linear thermal transmittance of the edge, Y, $W/m^{-1}K^{-1}$ was derived from comparison with a construction without thermal bridge. Thorsell and Källebrink arrived at Y-values in the range between 0,01 and 0,024 $W/m^{-1}K^{-1}$.

The effects of the thermal losses at the edges on the overall performance of the panel, however, are also affected by the area to perimeter ratio, that is the bigger the panels the smaller the effect of the thermal bridges at their edges (Ghazi Wakili et al, 2005).

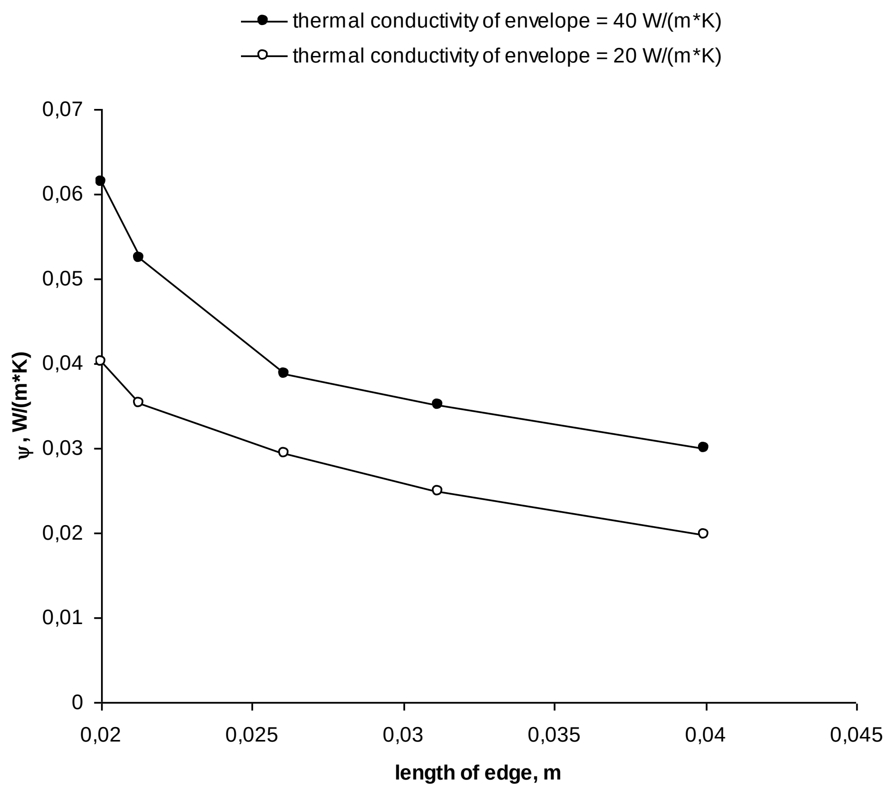

Figure 6. The linear thermal loss at the joint, ψ as a function of the length of the edge.

4. CONCLUSIONS

While VIPs offer an exciting and economically feasible alternative to traditional insulation materials it is of uttermost importance to secure their performance through the lifetime. Full metal envelopes can provide the means for just that.

As expected, the results indicate that the thermal loss at the joint of two VIP panels is drastically reduced by lowering the thermal conductivity of the envelope, the edges being of primary importance. Furthermore it can be concluded that a more robust cover, allowing a higher degree of vacuum and less subject to mechanical damage, can be applied with minimum consequences for thermal bridges.

Furthermore the thermal edge loss can be seriously reduced by lengthening the edge and can easily be compensated with an adjacent layer of thermal conductivity in the range of traditional insulation materials.

Further work is beyond the optimization of these factors but will involve the construction of a prototype followed by laboratory testing.

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Explanatory notes

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* The net cost of applying the vacuum insulation panels per sqm outer wall and year, C_{net}, is equal to

C_{net} = $C_{ins} \cdot A_{factor} + I_{rent}$, SEK $m^{-2}year^{-1}$

Where

C_{ins} = Cost of replacing traditional insulation with VIPs

I_{rent} = The rental income gained by additional space,

A_{factor} = The annuity factor,

Where the annuity factor, A_{factor}, relates the periodic payment to the present value of an investment and does therefore depend on the number of periods (years) and the modified interest rate, r_{mod}, based on the nominal interest rate and inflation as well as the rate of energy price change

$$A_{factor} = \frac{r_{\mathrm{mod}}}{1-(1+r_{\mathrm{mod}})^{-n}}$$