Minimize Thermal Edge Losses with Stainless Steel Envelopes for Vacuum Insulation Panels (VIPs).

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ABSTRACT

Vacuum Insulation Panels (VIPs) traditionally maintain a reduced pressure in their interior by surrounding a core with an inexpensive laminate of a polymer film with a 7.6 μm thick aluminum film, or a more expensive polymer film coated with ~0.3 μm thick aluminum film. In either case the VIP is too fragile to be attached directly to a building's envelope without utilizing a mechanical superstructure, and thermal edge losses of the superstructure can dramatically reduce the high R value offered by a VIP. We show that commercially available 51 μm thick stainless steel foil has the strength to be attached directly to a building's envelope without a superstructure, is relatively impermeable, and has edge losses between that of an inexpensive laminate and the coated film. We use a finite difference method to estimate how low the edge losses can be reduced. The economic justification for this reduction diminishes after achieving ~85% of the maximum R value for an infinite panel that would not have any edge losses.

Keywords: vacuum insulation panels, VIPs, edge losses, retrofitting building envelopes.

1 RETROFIT BUILDING ENVELOPES

Retrofitting costs can be minimized if a VIP is strong enough to be attached directly to a building without a superstructure, and if siding can be attached directly to the VIPs. The siding can protect the VIP from hail damage but the VIP still has to withstand wind shear. In a 190 km/hr wind the shear force (σ_{shear}) is 2.5 kPa.[1] As long as the VIP's vacuum is maintained, the outer surface is held on with 101 kPa, however, if the vacuum is lost the VIP becomes a thin bag filled with a fumed silica core. The wind shear force would then have to be resisted by the VIP edges, and for a panel that is much longer than it is wide ,

$$\sigma_{shear}*W=\sigma_{max}*2*t_{SS} \quad (1)$$

The panel's width is W, and the core is surrounded by stainless steel with thickness t_{SS}. Using a conservative 100 MPa for the maximum stress that stainless steel can withstand, then with a 51 μm thickness the maximum width is over 4 m. Stainless steel foil this thin is commercially available in ~1.2 m wide rolls, and that will be taken as the maximum practical width of the panel.

Atmospheric gasses can permeate through the VIP. The gasses N_2, O_2, and H_2O will permeate as molecules as described by equation 2

$$\dot{Q}_{perm} = k_{perm} * \frac{Area}{thickness} * \left(p_{atm} - p_{VIP}\right) \quad (2)$$

while a gas like hydrogen will dissociate and permeate as described by equation 3 [2]

$$\dot{Q}_{perm} = k_{perm} * \frac{Area}{thickness} * \left(\sqrt{p_{atm}} - \sqrt{p_{VIP}}\right) \quad (3)$$

At room temperature permeation through metals especially stainless steel and aluminum can typically be neglected. Nitrogen can permeate through steel (which is more permeable than stainless steel) at $\frac{3.7*10^{-13}}{m^2}*\frac{mbar*L}{s}$ if one atmosphere pressure differential is applied to a container with 1 mm thick walls at 52^{o}C. At this permeation rate a 2.5 cm thick VIP at zero pressure with 51 μm thick walls (two surfaces) will reach 1.3 Pa in 740 years.[3] Hydrogen has the highest permeation rate through stainless steel of all the atmospheric gasses, but it's pressure in the atmosphere is 0.05 Pa [4] and can be neglected since the VIP is effective as long as its internal pressure is below 1.3 Pa. Corrosion can appear as permeation[5] and must also be prevented.

Edge losses are proportional to the thermal conductivity of the edge times its thickness. Aluminum and stainless steel have thermal conductivities of 240 and 16 W/(m*K), respectively. The product of $\kappa_{Al}*t_{Al}$ is twice the value of $\kappa_{SS}*t_{SS}$ with 7.6 μm and 51 μm thick films, and the product of $\kappa_{Al}*t_{Al}$ is one tenth the value of $\kappa_{SS}*t_{SS}$ when the total Aluminum thickness is 0.3 μm.

2 EDGE LOSS MODEL

A 2.5 cm thick fumed silica core can have an R value of ~9.7 m^2*K/W,[6] and a tensile core of the same thickness can have a considerably higher R value of 26 m^2*K/W.[7,8] The thermal edge losses of a panel decrease the effective R value. These losses can be reduced but not eliminated by increasing the heat path, and the panel's gometry under consideration is shown in Figure 1. The cost of this performance improvement is the additional stainless steel foil required for the indicated jog and the additional manufacturing complexity.

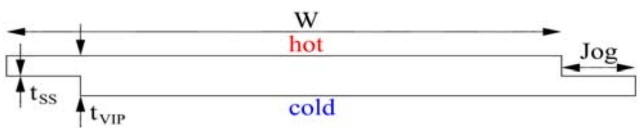

Figure 1 – A VIP with width W and thickness t_{VIP}, can minimize edge losses with the indicated Jog. The edge losses are from heat flowing through the stainless steel with thickness t_{SS}.

Thermal modeling of the heat flow is challenging because of the large difference between the VIP and stainless steel thickness, t_{VIP} and t_{SS} respectively. The model uses 0.00262 and 16 W/(m*K) for the VIP core (κ_{core}) and stainless steel (κ_{SS}) thermal conductivities, and assumes a thermal short along the hot and cold surfaces of the VIP. A 170x170 node array is used to model a jog surrounded on each side by half the panel's width. The model is schematically indicated in Figure 2. The thermal contact resistance between the panels and between the stainless steel and core is neglected. The reduction in heat flow for a 120 x 30 cm^2 VIP area is plotted in Figure 3, and the lowest heat flow never reaches the value for a VIP without edges, even with a 58 cm jog.

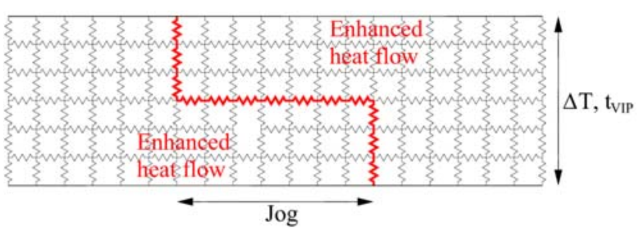

Figure 2 - The numerical model lumps all of the thermal resistance between the nodes into a discrete resistance, and then solves a set of simultanous equations to determine the heat flow within each loop. The red resistors are for the stainless steel edge and are thermal shorts compared to the black resistors for the VIP core. Enhanced heat flow regions are indicated and are adjacent to the thermal shorts.

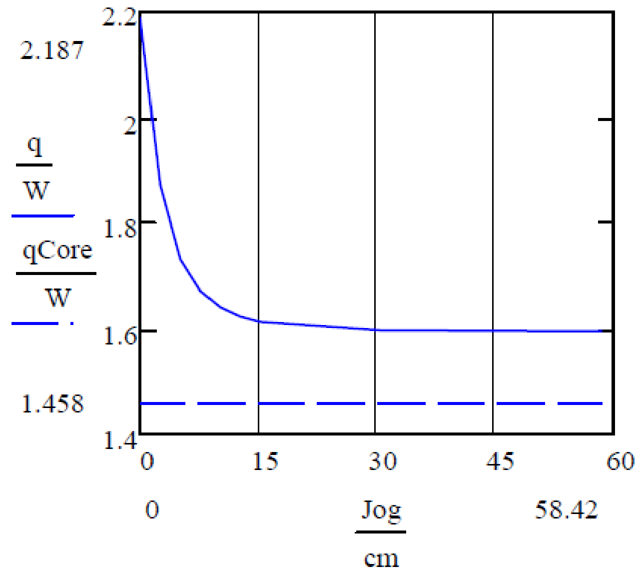

Figure 3 - The heat flow in a 120 cm x 30 cm section of VIP with 38 K applied across the VIP. The heat flux drops to 1.61 W at 15 cm, and decreases to 1.59 W at 58 cm. The heat flow without any edges is 1.46 W. The additional heat flow with a straight edge (jog = 0) is 0.73 W.

As shown in Figure 3, after a 30 cm jog diminishing returns are reached for the heat flow in a 120 cm wide VIP section that is 30 cm long. The heat flow never reaches the value without an edge because there is a thermal short across half the VIP thickness at the start and end of the jog. The enhanced heat flow adjacent to both thermal shorts is given by equation 4 which estimates that each thermal short drives the additional heat flow through a single edge into a strip with width t_{VIP}, and length L. The full temperature drop is assumed to be across the unshorted portion of the core, $0.5*t_{VIP}$.

$$\Delta Q = 2 * \kappa_{core} * t_{VIP} * L * \frac{\Delta T}{0.5 * t_{VIP}} \quad (4)$$

The heat flow through the core of the VIP is given by equation 5 where it is for a strip of width W (half the panel's width on each side of the jog is associated with each edge).

$$Q = \kappa_{core} * W * L * \frac{\Delta T}{t_{VIP}} \quad (5)$$

The ratio of these terms is given by equation 6.

$$\frac{\Delta Q}{Q} = \frac{4 * t_{VIP}}{W} \quad (6)$$

The estimate from equation 6 is for an 8% increase for a sufficiently large jog for a 120 cm wide VIP that is 2.5 cm thick. The numerical model indicates a 9% increase in heat flow.

An estimate of the point where the jog length reaches diminishing returns is when the enhanced heat flow at one end of the jog (half of equation 5) equals the heat flow down the jog through two thicknesses of stainless steel from adjacent VIPs. The estimate assumes the full temperature drop is across each thermal path. This is shown in equations 7 and 8 which predicts that diminishing returns are reached at ~31 cm. This estimate agrees with Figure 3.

$$\kappa_{SS} * 2 * t_{SS} * L * \frac{\Delta T}{Jog} = \kappa_{core} * t_{VIP} * L * \frac{\Delta T}{0.5 * t_{VIP}} \qquad (7)$$

$$Jog = \frac{\kappa_{SS} * t_{SS}}{\kappa_{core}} \qquad (8)$$

3 PAYBACK PERIOD

Since the width of commercially available stainless steel is limited to ~1.2 m, then increasing the jog length means reducing the width (W) of the panels which increases the edge losses. This constraint on panel's width leads to a maximum for the R value as shown in Figure 4 of ~8.2 m^2*K/W for a 10 cm long jog.

The jog in the VIP's edge increases the material costs of a VIP by requiring a third layer of stainless steel foil for the jog. The foil costs approximately \$5.40/m^2 in quantity. The fumed silica is estimated to cost ~\$16/m^2 for a 2.5 cm thick panel.

The payback period for retrofitting a building depends on the HDD (heating degree days w.r.t. 65^{o}F), CDD (cooling degree days w.r.t. 65^{o}F), $COP_{heating}$ (coefficient of performance for heating), $COP_{cooling}$, price of energy consumed, and R value prior to retrofitting. The computation of energy saved is in equations 9 and 10.

$$Energy_{heating} = \left(\frac{1}{R_{before}} - \frac{1}{R_{after}}\right) * \frac{HDD}{COP_{heating}} * 24\frac{hr}{day} \qquad (9)$$

$$Energy_{cooling} = \left(\frac{1}{R_{before}} - \frac{1}{R_{after}}\right) * \frac{CDD}{COP_{cooling}} * 24\frac{hr}{day} \qquad (10)$$

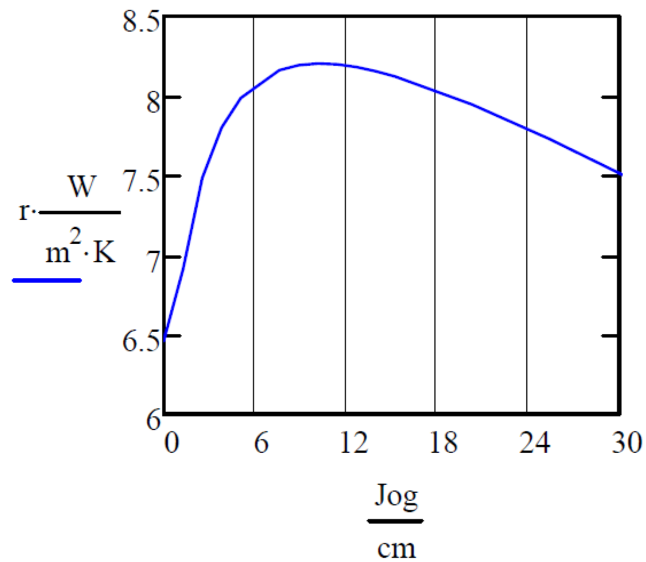

Figure 4 – Plot of R value in m^2*K/W vs. jog distance for a VIP with a fumed silica core that is 2.5 cm thick. When maximum foil width is 120 cm the maximum R value is 8.2 m^2*K/W with a jog of 10 cm. This is 85% of ideal fumed silica VIP without edges.

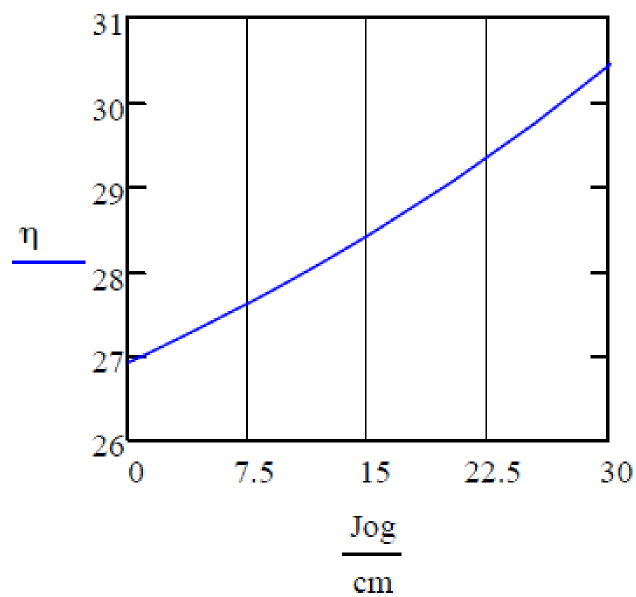

Figure 5 – VIP material cost per m^2 of VIP. As the length of the jog increases it requires more stainless steel.

The shortest payback period is for a building that is being covered with siding. The minimum incremental cost in that situation for adding VIP insulation is indicated in Figure 5. The payback period vs. jog length is in Figure 6 for buildings in Minneapolis and Miami. In each city buildings are considered with minimal and standard envelope insulation. The assumed coefficient of performances are 0.85 for a combustion furnace, and 2.5 for an air conditioner. Buildings with low R value in their envelope usually do not have the most efficient heating and

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cooling equipment. The HDD and CDD are 8002, and 634, for Minneapolis, and 141, and 1427 for Miami.[9] The average residential price of energy in 2010 was \$1.34/therm[10] (therm = 10^5 BTU = 106 MJ) for heating and \$0.116/kWhr[11] (kWhr = 3412 BTU = 3.6 MJ). Using these numbers the payback period vs. jog length is shown in Figure 6.

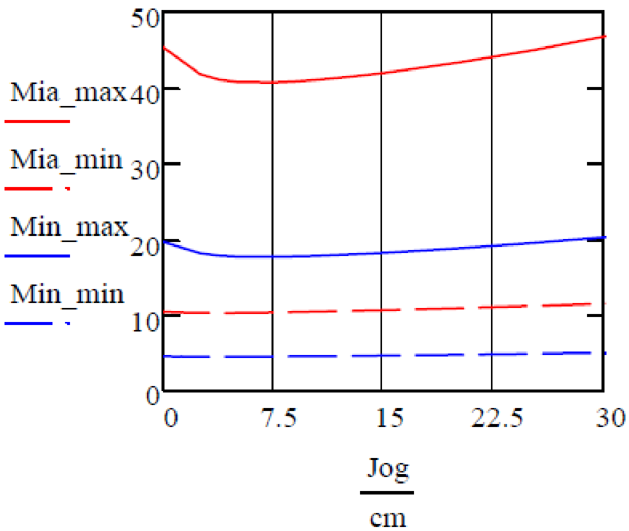

Figure 6 – Payback period in years for four cases. Mia_max, and Min_max are for buildings in Miami and Minneapolis respectively with envelopes that have an R value of 2.6 m^2*K/W. Mia_min, and Min_min are for buildings in Miami and Minneapolis respectively with envelopes that have an R value of 0.88 m^2*K/W.

4. CONCLUSIONS

We have shown that 51 μm thick stainles steel foil has the mechanical strength to be attached directly to a building's envelope and support a layer of siding, and should be impermeable to atmospheric gasses. The edge losses with the stainless steel foil can be reduced by placing a jog in the VIP's edge. A model is developed to evaluate the edge loss reduction, and with a 10 cm jog the edge losses are reduced so that the panel achieves ~85% of the theoretical R value for a panel without edges. The minimum payback period of a 2.5 cm thick VIP depends on the energy consumption, and is easily justified when siding is going to be attached to a building with poor insulation.

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