

Kjartan Gudmundsson and Peyman Karami

Department of Civil and Architectural Engineering, Royal Institute of Technology (KTH), Stockholm 100 44, Sweden

Abstract: Vacuum insulation panels provide unprecedented possibilities for renovating the existing building stock in a manner that reduces the thermal losses through the building envelope. This study is focused on the implementation of VIPs (vacuum insulation panels) in energy retrofit projects with rendered outer walls. Particular emphasis is put on reducing the thermal bridges due to mechanical fasteners and at the joints of the panels. These are evaluated through a parametric study of the impact of the thermal conductivity of the joints of the panels and the adjacent insulation layer as well as the material of the fasteners. The study is carried out with 3D FEM (finite element method) simulations software. Furthermore, the moisture conditions in the construction are studied. The dynamic moisture behavior of a wall construction is modeled with a two dimensional FEM model. The long term effects of vapor diffusion are investigated in terms of accumulated moisture and the risk of condensation. The results illustrate that vacuum insulation on the outside of the wall construction does not pose a moisture problem to the construction. The simulations are based on a draft of a new technical solution for the refurbishment of a building that is typical for the great Swedish building program of the 1970s.

Key words: Vacuum insulation panels, retrofit project, thermal bridges, parametric study, moisture conditions, FEM model.

1. Introduction

The transmission losses through the climatic envelope represent about half of the energy used for space heating, and a substantial share of the total energy use in Sweden. A reduction of the heat losses through the walls, floors and roofs of the buildings must therefore be a part of the strive towards reducing the energy use, in benefit of environment and economy. If conventional insulation materials are to be used, the result will be a significant increase in the thickness of the climatic envelope. A house in Sweden, that is to meet the passive house standards, for instance, would have to have an insulation thickness of more than 330 mm in the wall in order to meet a U-value of 0.10 $(W \cdot m^{-2}K^{-1})$. Consequently, significant living space area may be lost and restrictions are put on architectural possibilities. In terms of refurbishing, there is often too little space available on the inside of the building and the application of external insulation may threaten the architectural values of the facades and pose problems in terms of detailing.

The unique insulations properties of vacuum panels may, however, provide new opportunities since only a fraction of the insulation thickness is required.

The application of vacuum insulation has been limited to a fairly small number of buildings. An account of their use can, for instance, be found in the report of the International Energy Agency [1], Wakili et al. [2] and Binz and Steinke [3].

1.1 VIPs and Thermal Bridges

The in situ performance of VIPs (vacuum insulation panels) depends on the properties of the panels and the manner in which they are applied. The joints at which the panels meet give rise to thermal bridges that

Corresponding author: Kjartan Gudmundsson, Dr., assistant professor, research fields: analysis and assessment of constructions with respect to the transfer of heat and moisture, project of vacuum insulation panels and their application and development. E-mail: kjartan.gudmundsson@byv.kth.se.

increase the heat loss through the building envelope. Analytical models for high barrier laminates around VIPs are to be found in the work of Tenpierik and Cauberg [4] while Thorsell and Källebrink [5] looked at the effects of applying a serpentine edge on a metal panel. Others have investigated the different thermal bridges that arise when VIPs are applied in constructions and building details [2, 6-8]. Our previous parametric studies show that the thermal edge loss can be compensated with an adjacent layer of thermal conductivity in the range of traditional insulation materials [9].

1.2 Moisture Conditions

Excessive moisture is arguably the greatest single threat to the durability of buildings. The implementation of a new building technology must therefore await a thorough analysis of the moisture performance of the construction, including an evaluation of the risk of condensation and high relative humidity.

Brunner and Simmler [10] did an in situ performance assessment of VIPs in a flat roof construction, with measurement above and below the panels as well as at the joints. Johansson [11] did an assessment of a timber wall construction from the 1930s, retrofitted with exterior vacuum insulation panels, concluding that the moisture content of the wall is expected to decrease after retrofitting and Sveipe et al. [12] did investigations of improving thermal insulation of timber frame walls by retrofitting with vacuum insulation panels, finding that exterior VIPs may at certain conditions cause condensation in the wall. Buxbaum et al. [13] studied the hygrothermal performance of external masonry walls with inside insulation systems made of VIP sandwich panels. Other work includes laboratory investigations based on hot box a measurement and comparisons with numerical simulations for several wall structure arrangements retrofitted with vacuum insulation panels [14]. Lichtblau [1] did a thermal performance assessment of a wooden construction in a "lowest-energy" semi-detached house in Munich that was retrofitted with VIPs on exterior walls, roof and front door. Previous research also includes an assessment of a jamb-crossbar construction with vacuum insulation panels in a newly-built extension of the Erlenbach Hospital, the aim of which was to install elements with the same thickness as insulated windows panes [1].

2. The Implementation of VIPs in a Retrofit Project

Due to its vast capacity, the current building stock in Sweden must be included in the effort to reduce the energy used for heating. The million unit program in Sweden is of special interest. The million unit program is a common name for about one million housing units that were built in a 10 year period around the 1970s, many of which are now in dire need of retrofitting, not at least in terms of thermal insulation. With a high degree of repeatability, it may be argued that the program has a high potential to gain from thorough studies and development of technical solutions for refurbishment.

The area of Hovsjö, south of Stockholm, is a typical representative of the program, with 2,200 apartments in mostly three to eight storey buildings. With an outer wall construction of light aggregate concrete blocks, as illustrated in Fig. 1, the thermal insulation is far below today's requirements.

This study investigates the possibilities of using VIPs for improving the thermal insulation of the wall construction while addressing the issue of thermal bridges at the joints at which the panels meet as well as due to mechanical fasteners. Of particular interest is a solution with an insulation material adjacent to the VIPs on the outside, that may limit the thermal bridges while protecting the panels and providing a carrier for the rendering of the facade.

The aim is to investigate how the heat flux through the construction is affected by the thermal conductivity



Fig. 1 Hovsjö, an example of a housing project in the million unit program [15].

of the material in the gap where the panels meet and furthermore how the heat flux is influenced by the thermal conductivity of the adjacent insulation and the thermal conductivity of the fasteners. The moisture distribution and the relative humidity in the wall construction are also studied for a long term exposure to extreme conditions as well as a reference climate for Stockholm.

The retrofit solution, shown in Fig. 2, consists of an existing light aggregate concrete wall with an added outer insulation of vacuum insulation panels on top of which there is an insulation layer that serves to protect the VIPs and provides a foundation for the rendering of the wall. The joint at which the panels meet is filled

Table 2Parameters and the range of study.

with insulation material. A mechanical fastener, at the corners where the panels meet, keeps the adjacent insulation in place.

The thermal and hygric properties of the different materials are shown in Table 1. The table shows the default values of the study while the authors want to investigate the potential gains of altering the thermal properties within the range shown in Table 2. The thermal calculations have been carried out with one equivalent layer in the envelope with a total thickness equal to the sum of the thicknesses of the aluminium layers in a multilayer foil.

The water vapour permeability is an equivalent value for an arbitrary modelling thickness of 1 mm derived from the values of the water vapour transmission rate presented in Ref. [16].

The sorption curves of the light aggregate concrete and the fumed silica core are dealt with by linear approximations of data from Refs. [16, 17].



Fig. 2 Vertical cross section of a proposed technical solution for refurbishment of the construction.

Table 1 Material layers, thermal conductivity and water vapor permeability.

Material layer	Thickness (mm)	Thermal conductivity $(W \cdot m^{-1} \cdot K^{-1})$	Water vapor permeability $(10^6 \text{ m}^2 \cdot \text{s}^{-1})$
Rendering	15	1.0	1
Mineral wool	45	0.04	20
VIP core	50	0.005	20
VIP envelope	0.0003	200	1.1×10^{-5}
Material at the joint of panels	50	0.1	20
Light aggregate concrete	160	0.14	4
Stainless steel bolt	5 mm diameter	20	-

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Parameter			Range ($W \cdot m^{-1} \cdot K^{-1}$)
Thermal conductivity of bolt			5-200

Thermal conductivity of bolt	5-200
Thermal conductivity of joint	0.02-0.1
Thermal conductivity of adjacent mineral wool	0.02-0.04

The light aggregate concrete was estimated to have a moisture content that increases linearly according to Fig. 3, while the fumed silica of the core is assumed to have a moisture content that increases linearly from zero at totally dry conditions to 32.4 (kg·m⁻³) at 100% relative humidity.

3. Calculation Model

The calculations of the heat transport are based on the heat equation that in one dimension can be written as:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c} \cdot \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where, *T* is the temperature (K), *t* is the time (s), λ is the thermal conductivity (W·m⁻¹·K⁻¹), ρ is the density (kg·m⁻³) and *c* is the specific heat capacity (J·m⁻¹·K⁻¹).

The simulation of the moisture transport is carried out with a transient diffusion model that in one dimension can be written as:

$$\frac{\partial C}{\partial t} = D_C \frac{\partial^2 C}{\partial x^2} - \frac{\partial S}{\partial t}$$
(2)

where, *C* is the concentration of water vapor in the material (kg·m⁻³), D_C is the water vapor diffusivity (m²·s⁻¹), in the porous material, *x* is the distance in the direction of the flow (m) and *S* is the amount of adsorbed water in the material (kg·m⁻³).

The sorption curve can be approximated with a piecewise linear function, that in an interval (*i*) can be written as:



Fig. 3 The linear approximation used to describe the sorption isotherm of the light aggregate concrete.

$$S = a + k_i \frac{1}{C_{sat}(T)}C$$
(3)

where, *a* is a constant denoting the amount of adsorbed water vapor at the breaking point of the curve (kg·m⁻³), k_i is the gradient of the sorption curve in the interval (kg·m⁻³), *i*, that is the ratio between the change in moisture content and the change in relative humidity that equals the concentration of water vapor at saturation C_{sat} , (kg·m⁻³).

The rate of adsorption can therefore be written as:

$$\left(\frac{\partial S}{\partial t}\right)_{i} = k_{i} \frac{1}{C_{sat}} \left(T\right) \frac{\partial C}{\partial t}$$
(4)

assuming that hygroscopic equilibrium is reached at an instant.

The diffusion equation thus becomes:

$$\frac{\partial C}{\partial t} = \left(\frac{D_c}{\frac{k_i}{C_{sat}(T)} + 1}\right) \frac{\partial^2 C}{\partial x^2}$$
(5)

where, the gradient k_i is evaluated in each time step.

As the relative humidity increases, the transport rate of moisture may be enhanced through surface diffusion or capillary transport. While surface diffusion takes place at a relative humidity as low as 30%, capillary transport will occur as the critical moisture content is surpassed [18].

In the case of enhanced moisture transport above a certain relative humidity the total moisture transport can be written as the combination of ordinary diffusion and the diffusion of adsorbed water vapor:

$$g = D_C \frac{dC}{dx} + D_s \frac{dS}{dx}$$
(6)

where, the first term on the right hand side is the ordinary diffusion term while the second term describes the transport of the adsorbed water vapour and D_S is the enhanced diffusion coefficient for the combined effect of surface diffusion and capillary transport (m²·s⁻¹). A diffusion process that is accompanied by adsorption of the water vapour can be written as:

$$\frac{\partial C}{\partial t} = D_C \frac{\partial^2 C}{\partial x^2} - R \tag{7}$$

where, *R* is the rate of removal for the water vapour that is adsorbed by the porous material $(kg \cdot m^{-3} \cdot s^{-1})$. In a similar manner, the diffusion equation for the transport of the adsorbed water can be written as:

$$\frac{\partial S}{\partial t} = D_s \frac{\partial^2 S}{\partial x^2} + R \tag{8}$$

where, the reaction rate of water appearing in liquid phase equals the removal rate for the water vapour that can be described by the following equation:

$$R = \frac{k_i}{C_{sat}} \frac{\partial C}{\partial t} - \frac{C_{sat}}{k_i} \frac{\partial S}{\partial t}$$
(9)

The reaction rate is thus determined by the relative humidity in the pores and the water content in the material.

4. Results

Thermal calculations were carried out with a stationary 3-dimensional FEM model with Comsol Multiphysics[®]. The thermal model assumes indoor and outdoor temperatures of 20 °C and 0 °C, respectively. The panels have a dimension of 40 cm by 40 cm while the boundaries are placed at the line of symmetry at the middle of the panels, providing with zero heat flux boundary conditions.

The moisture distribution in the wall section was carried out in Comsol Multiphysics® with transient two dimensional models. The indoor temperature and relative humidity are as defined by EN 15026, while the average hourly values for outdoor temperature and relative humidity are retrieved from an IWEC (international weather for energy calculation) climate file for Stockholm. The initial vapor content of all the different materials is assumed to correspond to the moisture content of the exterior air, except for the vacuum insulation panel, the initial moisture content of which is assumed to be zero. The simulations are carried out for a period of one year. As the relative humidity exceeds 80% the core material has an enhanced diffusion coefficient, D_S , with an arbitrary value of five times the ordinary diffusion coefficient, thus allowing for the redistribution of the adsorbed water vapor.

4.1 Resulting U-Values

The following results are to be measured against the performance of a construction with no thermal bridges. For a construction with no thermal bridges other than the edges of the panels the calculated resulting U-value is 0.09 (W·m⁻²·K⁻¹).

The total heat flux done is obtained by integrating over the area of flow, that is in the xz-plane of Fig. 4, and consequently the flow per unit area and unit temperature difference can be calculated. The results are shown in the following, starting with the diagram of Fig. 5that shows how the thermal conductivity of the fasteners affects the resulting U-value of the wall construction. The red solid line shows that the influence of the bolts is almost negligible in the case of a light aggregate concrete wall, in contrast to the results



Fig. 4 Results from a 3D simulation of the heat flow in the wall section.





Fig. 6 The resulting U-value of the section as a function of the thermal conductivity of the joint material.

for a massive concrete wall as illustrated by the blue dotted line. It is also of interest to study the influence of the material of the joint. As shown in Fig. 6, the effect of using a joint material with low thermal conductivity has a significant effect on lowering the heat loss through the material. Going from a value of 0.10 $(W \cdot m^{-1} \cdot K^{-1})$ to a value of 0.02 $(W \cdot m^{-1} \cdot K^{-1})$ will give a reduction that amounts to about 30% of the total heat loss.

The insulation layer on the outside of the VIPs provides protection for the panels and serves as a substrate for the rendering. As shown in Fig. 7, the influence of improving the outer insulation layer has a significant effect on the heat flux, although somewhat less than the effect of lowering the thermal conductivity of the joint.

4.2 Moisture Profile

The model can be used to investigate the moisture profile of the construction at long term exposure to rather extreme conditions, i.e. a temperature of -10 °C out of doors and 20 °C on the inside. It is of special interest to investigate the risk of high relative humidity at the joints of the panels, since they are subject to a temperature distribution that differs from that of the homogenous wall section in the one dimensional simulation. This is done through a 2-dimensional transient simulation of the wall section, the results of which are shown in Fig. 8.

The concentration gradient climbs from zero within the panel towards the ambient on both sides and the foil has a moisture resistance of several magnitudes greater than that of the other materials. The vapor content of the wall on the inside of the panel will therefore slowly approach the vapor content of the interior surroundings. In a similar manner, the vapor content on the outside of the panels will reach that of the exterior. The superior thermal properties of the VIP ensure that the temperature throughout the light aggregate concrete on the inside will be in the vicinity of the indoor temperature and consequently the relative humidity on the inside of the panel will not supersede the relative



Fig. 7 The resulting U-value of the section as a function of the thermal conductivity of the adjacent insulation.



Fig. 8 The relative humidity distribution in the wall construction at long term extreme conditions.



Fig. 9 Relative humidity in the wall construction as a function of time.

humidity of the indoor air. By a similar argument, it may be concluded that the relative humidity on the outside of the panel will be close to the relative humidity of the outdoors. The temperature at the joints on the inside of the panels was also investigated with a bolt in the construction. With a stainless steel bolt the temperature was found to be around 12 °C while 15 °C without a bolt at the joint, in both instances well above the dew point for the actual vapor content.

The moisture behavior of the construction was also investigated when subject to climatic conditions of Stockholm. Fig. 9 illustrates the variations in relative humidity in selected points (Fig. 8).

In principle, the findings depicted in Fig. 9 are in agreement with the simulations at constant boundary conditions on the inside and the outside. The relative humidity is therefore fairly low but a phase lag and dampening due to sorption can be detected between the interior climate and the concrete wall.

5. Conclusions

This study is concerned with the thermal performance of a refurbished outer wall of light aggregate concrete with exterior vacuum insulation panels. One option of particular interest is that of rendering on an insulation layer on the exterior of the VIPs. The simulations show that, while the VIPs have superior insulation properties, the detailing must be given a careful consideration. Using a material of relatively low thermal conductivity at the joints at which the panels meet has a significant effect on the resulting U-value of the construction. The thermal conductivity of the adjacent insulation layer has a notable effect on the heat flux, but the choice of material for the fasteners does not have a noteworthy effect on the resulting U-value.

The moisture performance of the construction was evaluated with a transient diffusion model that allows for sorption in the material as well as enhanced moisture transport at high relative humidity. A calculation of the relative humidity illustrates that the placement of the vacuum insulation on the outside of the wall does not pose a moisture problem to the construction. Furthermore, it has been shown that there is no risk of high relative humidity at the joints of the panels. The model does not take into account the penetration of rainwater and leakage through the joints of the panels and further work must take this aspect into consideration.

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