Vacuum insulation panels (VIPs) for use in buildings

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Abstract

Through the ReCO$_2$ST project, vacuum insulation panels have been installed on the demonstration building at Brunel University London and are being monitored for thermophysical performance. First results show monthly average temperatures in the range of 12.8 °C – 15.8 °C between the wall and the insulation layer when monthly average ambient temperature was 5.6 °C. A new submicron-scale polymer foam has been characterized for use in vacuum insulation panels. FT-IR results regarding radiative conductivity and specific extinction with and without graphite opacifier are presented. The thermal conductivity as function of gas pressure has also been investigated. This new materials has achieved a thermal conductivity of approximately 5 mW/(m·K) under vacuum, similar to fumed silica. Thermal conductivity doubles at gas pressure of 50 mbar, making it less suitable as core material for long term applications unlike fumed silica, but more suitable than other known core material alternatives such as polyurethane or glass fiber.

Keywords: vacuum insulation, advanced porous materials, polymeric foam, FT-IR

1. Introduction

The European Union has set its goal to achieve climate neutrality by 2050. Currently the building stock is responsible for approximately 36% of Europe's CO_2 emissions and 40% of the final energy consumption for heating and cooling [1]. To improve energy efficiency of the building stock, existing and new build, thermal insulation is known to play a key role.

Several types of thermal insulation materials are available in the consumer market; thermal conductivity, an important performance index, for some of the commercial products is shown in Figure 1. One barrier for establishment of new technologies is user misinformation regarding the effectiveness of the solutions. Often consumers don't have full access to the accurate information about the potential performance and applicability of new technologies, and any new development is viewed with suspicion.

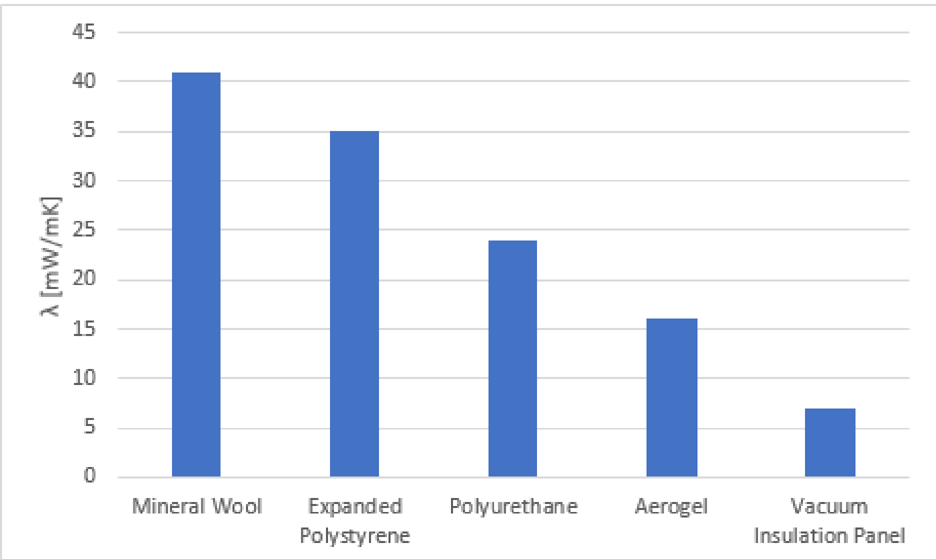

Figure 1: Thermal conductivity of five contemporary insulation materials.

To help decision makers in selecting the best energy efficiency interventions for a building, the ReCO2ST project has developed a retrofit assessment tool comprising of a retrofit kit containing a range of technologies [2]. Vacuum Insulation Panels (VIPs), see Figure 2, have been proposed as part of this kit owing to their thermal conductivity of 0.005 - 0.007 W/(m·K), the lowest among all insulation currently available. Due to their low thermal conductivity, vacuum panels require less thickness of insulation layer than conventional insulating materials to achieve a certain U-value. VIPs are therefore being used more and more often, especially in large cities where the available usable floor space is limited and the per square meter prices are high.

This paper describes the achieved performance of VIPs installed on external walls of a demo-building in Brunel University London (UK).

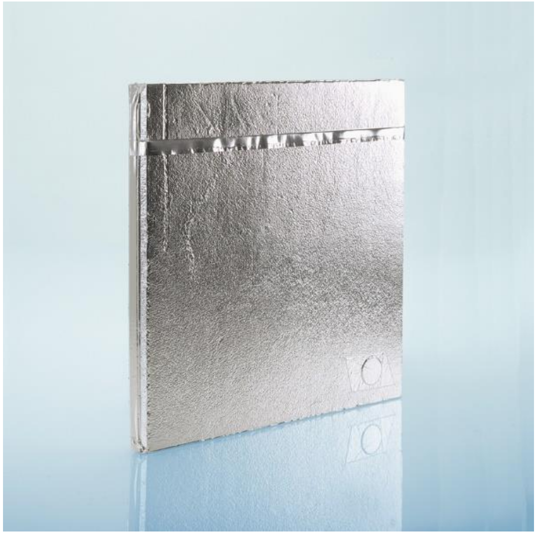

Figure 2: Vacuum Insulation Panel (VIP).

2. General description of VIPs

For insulation materials, the total thermal conductivity (λ) can be mathematically expressed by equation (1)

$$\lambda = \lambda_{solid} + \lambda_{gas} + \lambda_{radiation} \quad (1)$$

where

λ_{solid} is the thermal conductivity of the bulk material

λ_{gas} is the gaseous thermal conductivity

$\lambda_{radiation}$ is the radiative thermal conductivity

λ_{solid} can be reduced by using lower density core material, for example porous foams. The lower the density of a material, the lower the solid thermal conductivity it achieves. However, this often leads to an increase in the gaseous conductivity due to a larger amounts of gas (air) that can be contained in the pores of the material. Dormant air has a thermal conductivity of 0.026 W/(m·K). Using a different gas to fill present pores, λ_{gas} can be reduced, for example with pentane in polyurethane foam. The contribution of radiation to the thermal conductivity can be reduced by the addition of opacifiers, which absorb the energy and therefore inhibit the energy transportation through the material.

A principle to reduce all three terms of thermal conductivity, shown in equation 1, to a minimum is already demonstrated by the thermos flask. It contains vacuum in between a double wall. Its inside surface is mirrored to reflect thermal radiation from its contents back into the flask.

VIPs adopt the concept of the thermos flask with their rectangular cross-section being the point of difference. Due to internal vacuum, an external pressure of 10 t/m² acts on the VIP plate, which the thermos flask can only withstand due to its cylindrical structure. An evacuated plate therefore requires a support structure to withstand the atmospheric pressure and keep it in shape. Highly open porous materials are particularly suitable for this purpose in order to decrease solid conductivity to a minimum while being able to be evacuated [5]. Materials with a pore size smaller than 1 µm are particularly suitable. In this size range, heat transfer by air molecules is additionally inhibited, as this is below the so-called critical path length.

Fumed silica powder, which has been pressed into rigid boards is the most popular core material for VIPs for long term applications like in the construction industry. An opacifier is often added to the VIP core material to reduce heat exchange through radiation [6]. Magnetite or SiC are the most commonly used in combination with fumed silica.

A high barrier envelope made from a multi-layered metallized polymer film maintains the vacuum inside the panel. This barrier reduces the intake of air and water vapor below 1 mbar/year ensuring a long service life of the VIP. In the construction sector, the envelope is usually treated with a fire protective coating to meet the fire regulations for this industry. There is an additional dust protection fleece between the outer shell and the core. This serves as a filter element during the evacuation process. Figure 3 shows components of a VIP.

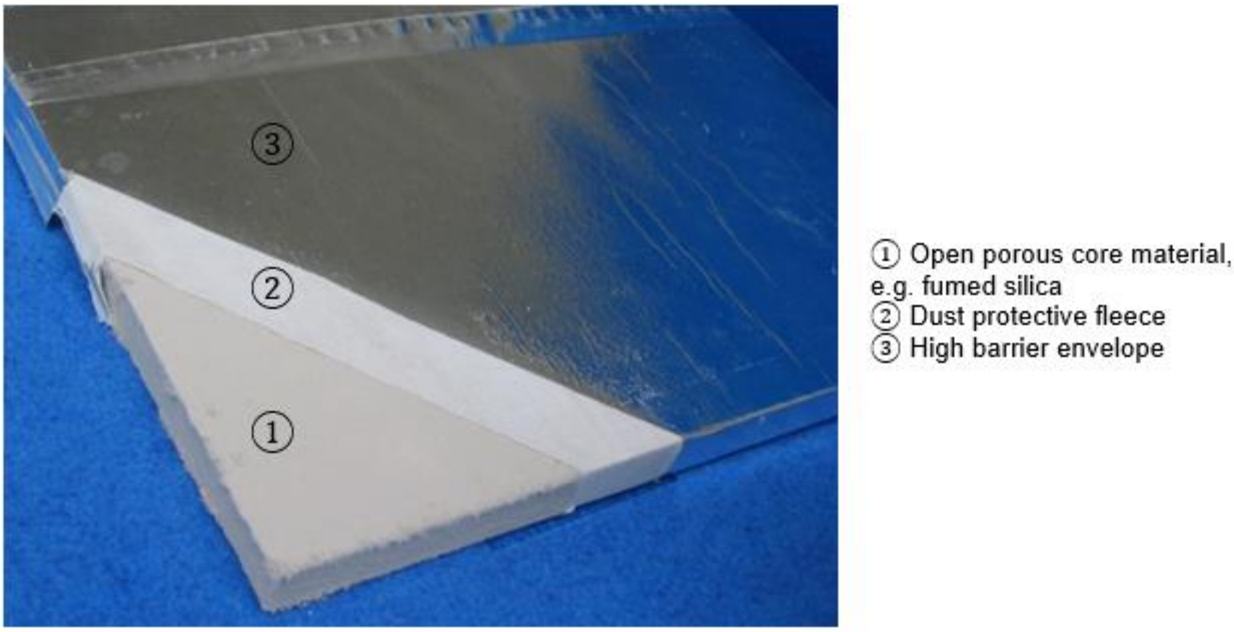

Figure 3: A vacuum insulation panel from va-Q-tec AG.

VIP technology offers up to ten times better thermal resistance compared to other insulation materials; just after manufacture its thermal conductivity is < 0.005 W/(m·K). Due to permeation of air and water vapour through the envelope thermal conductivity rises slowly over time eventually resulting in a declared thermal conductivity of λ_D = 0.007 W/(m·K). A permeation of < 1 mbar/year offers a service life of 60 years and more. Even if a VIP is fully ventilated with air it still offers a thermal conductivity of 0.020 W/(m·K) [8], which is still better than most conventional insulation materials. Furthermore, the silica core is inert and fully recyclable. After VIP has reached its end of service life, the core material can be retrieved and reused in a new VIP and the envelope can undergo standard plastic recycling.

The low thermal conductivity of VIPs makes them more and more relevant for metropolises. The increasing population of inner cities makes space limited and has led to a rising demand for new innovative insulation materials. For example, London is expecting more than 500 new high-rise buildings within the next decade [3]. This is where VIPs pay off specifically compared to other insulation materials. A decisive factor in the choice of the right insulation material is the specific cost. These are determined by the costs per m³ of the insulation material plus the costs for the usable volume of the building in which the insulation is installed. These can be particularly high in urban areas. This sum is then multiplied by the thermal conductivity of the insulation material as described by equation (2).

$$Specific\ Costs = [\frac{cost}{m^3}\,(insulation\ material) + \frac{cost}{m^3}\,(usable\ space)] \cdot \lambda \qquad (2)$$

Figure 4 gives an overview about the specific costs of different insulation materials for two scenarios: usable volume costs of 0 € and 1000 €. In rural areas, usable volume costs are low, since there is space available. Therefore, in terms of specific costs, conventional insulation materials like mineral wool, EPS or polyurethane offer the best cost/performance ratio. However, when the costs for usable space rise, like in big metropolitan areas, vacuum insulation panels become of more interest due to their high performance insulation properties. Due to their very low thickness, they allow very thin constructions, which make more space available.

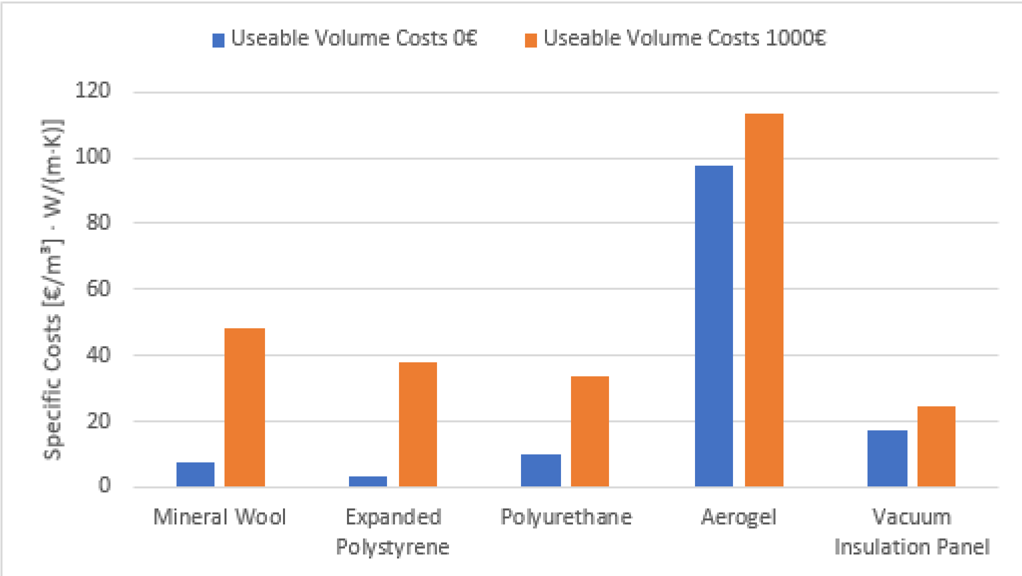

Figure 4: Comparison of specific costs of different insulation materials for different usable volume costs.

In addition to the construction sector VIPs are also used in many other applications areas where space is limited, but an excellent thermal insulation is required. They can enable refrigerators to use up to 50% less electricity to reach the highest energy class while they still keep their inner and outer dimensions [5]. Containers and transport boxes equipped with VIPs have been shown to provide up to five days constant temperature without an external power supply for the shipment of heat or cold-sensitive products. They can also be employed in the automotive and aviation sector.

3. Case study: Brunel University London

The VIPs were applied onto the external surfaces of two walls, North and South, on the ground floor of the Clifton R block of student accommodation, see Figure 5. The building orientation is such that North wall has no exposure to direct sunlight throughout the year whereas the South wall receives sunlight except early in the morning when it is partially shaded by an adjacent building.

The VIPs were installed by a bespoke methodology developed at Brunel University London and described in Jose et al. [9]. Nine VIPs each measuring 1000 mm x 600 mm x 30 mm were installed on the outer surface of walls. The installation at three different stages can be seen in Figure 6.

To measure the thermal performance of VIPs 27 k-type thermocouples were used with three colinearly located ones on each VIP, one at its centre on outermost surface facing the ambient, one at inside surface facing wall and one at the inner wall surface inside the room. The locations of thermocouples on the inner wall surface inside the room are shown in Figure 7. Thermocouples have been recording temperatures at a frequency of every 10 minutes since August 2019.

Figure 5: A view of the student accommodation façade that was insulated with VIPs at Brunel University London (UK).

Figure 6: Stages of VIP installation at Brunel demo building.

Figure 7: Thermocouple locations on the inner surface of wall inside the room.

Monthly average temperatures for January 2020 measured at eight locations by thermocouples sandwiched between VIPs and wall external surface are shown in Figure 8(a). Monthly average ambient temperature during this period was 5.6 °C. The benefit of having VIPs on walls in terms of higher wall outer surface temperatures than ambient temperature is clearly evident. Figure 8(b) shows on the right the thermographic image of the partially VIP insulated wall. The central blue rectangle is the area that was insulate by nine VIPs with the rest of walls left uninsulated. Temperature at the outermost surface the VIP, facing ambient, is recorded as -2.1 °C with the rest of the wall temperature being > 7 °C represented by green and yellow colours. The benefit of having VIP insulation can be interpreted as a saving of space heating energy that would be otherwise required to compensate the loss equivalent to a temperature of 9.1 °C.

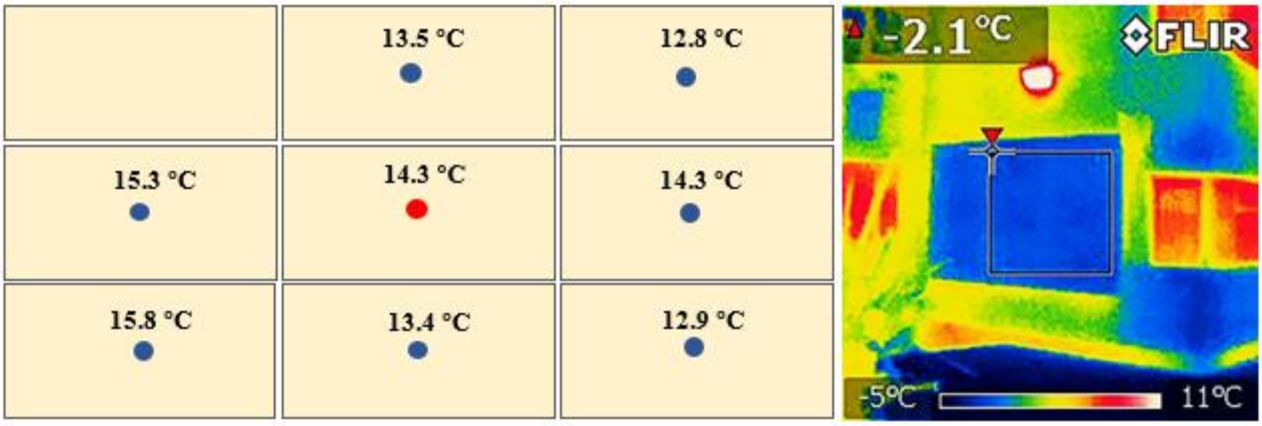

Figure 8: (a) Monthly average temperature on external wall surface insulated by VIPs for January 2020; (b) thermographic image of VIP insulated wall.

4. ReCO₂ST Development

Research is continuously ongoing to improve the performance of insulation materials, make them more cost efficient and reduce their carbon footprint. One of these developments is a submicron-scale polymer foam developed by the company SUMTEQ GmbH, based on a process developed by Strey et al. [4].

Following the methodology described in [6][9] specific extinction and radiative conductivity of the SUMTEQ foam with and without opacifier (graphite) was predicted using the transmission measured by a Perkin Elmer Spectrum One FT-IR Spectrometer over a spectral wavelength range of 5–15 nm at room temperature held at 20 °C. Results are shown in Figure 9. Due to difficulty in obtaining an optically thin film from the core material, KBr method was used. FT-IR scanning resulted in the transmittance as a function of wavelength from which specific extinction was calculated. The effect of opacifier is clearly evident from Figure 9.

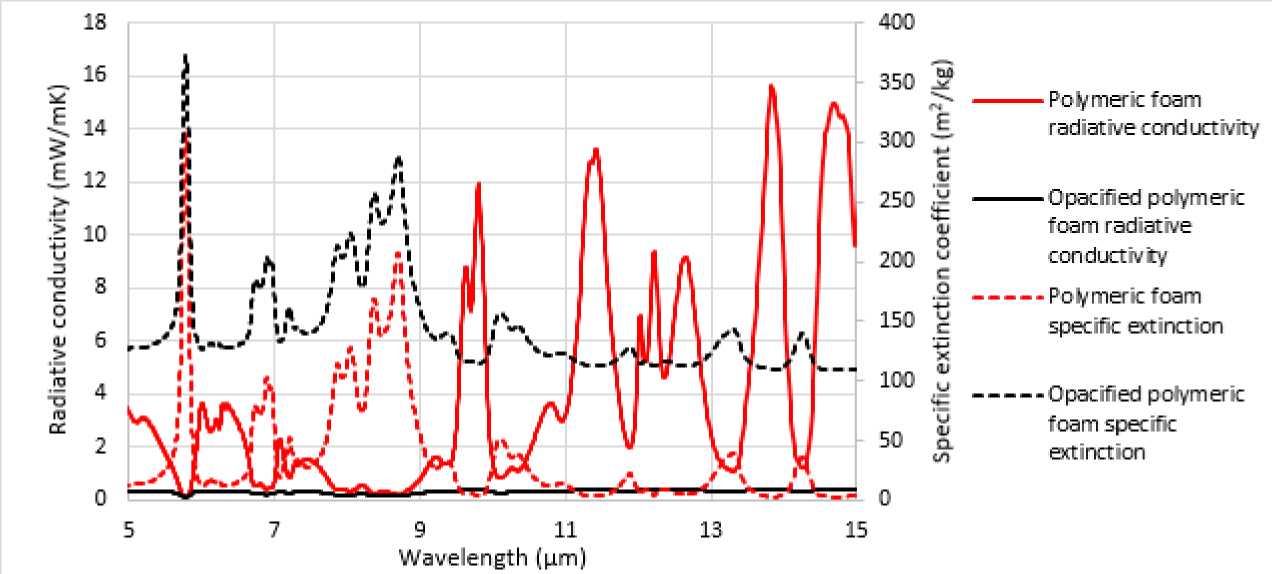

Figure 9: Measured specific extinction coefficient and derived radiative thermal conductivity of the VIP core.

This new core material has been characterized regarding thermal conductivity as a function of air pressure and compared to conventional core materials (Figure 10). This is an important characterization to study the suitability of core materials for use in VIPs. Fumed silica still shows the lowest dependence of thermal conductivity on air pressure. The thermal conductivity below 10 mbar is approx. 4 mW/(m·K) and doubles at a pressure as high as 100 mbar. In other core materials like polyurethane or glass fiber this happens already below 1 mbar.

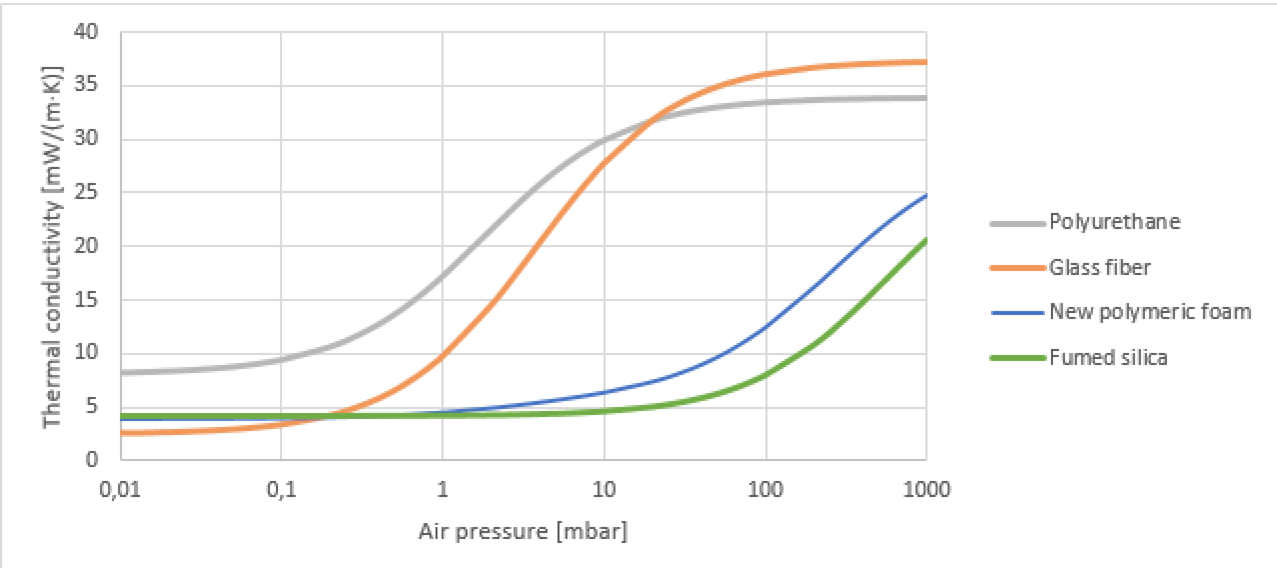

Figure 10: Thermal conductivity vs air pressure for different VIP core materials.

The difference in this behavior is caused by the different pore sizes of the materials. Polyurethane foam and glass fibers have a pore size of 130 µm and 60 µm respectively, whereas fumed silica has pores in the sub-micrometer scale of about 0.4 µm. This small pore size of fumed silica causes the so-called "Knudsen effect", which results in a reduction of thermal conductivity through gas (air in this case) when the size of the pore is in the same order of magnitude as the free path length of the gas molecules. In practical, it means that a relatively low vacuum is sufficient to suppress the thermal conductivity of air in the pores. Coarser-pored materials like polyurethane or glass fiber require air pressures below 0.1 mbar to reach their lowest thermal conductivity values.


Figure 11: VIP made from new polymeric foam.

The newest generation of the new polymeric foam and its properties as VIP (Figure 11) has been investigated within the scope of the ReCO_2ST project. This new material has a thermal conductivity in vacuum of about 5 mW/(m·K), similar to fumed silica. It also features small pore sizes below 1 µm, resulting in a thermal conductivity similar to still air under atmospheric conditions. However, there are still some gaps in the micrometer scale present between the particles, doubling the thermal conductivity at a pressure of about 50 mbar. This behavior is not as good as fumed silica in keeping thermal efficiency for a long service life. However, it is better than polyurethane or glass fiber (Figure 10).

5. Conclusion

A VIP installation on an existing building has been described along with their in-situ thermal performance. VIPs were found to have a huge potential of saving space heating energy consumed in uninsulated or partially or poorly insulated buildings like the one investigated in the ReCO_2ST project in London (UK).

First characterization results of a new sub-micron polymer foam for use in VIP have been presented. The addition of carbon black as opacifier reduces the radiative conductivity. The thermal conductivity shows values as low as fumed silica in vacuum, which doubles at 50 mbar. Whether this new material can be used in the future as a substitute for fumed silica depends also on other ageing effects and the future costs of large-scale production, which are still under investigation.

6. Acknowledgement

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7. References

[1] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018

[2] Residential Retrofit assessment platform and demonstrations for near zero energy and CO_2 emissions with optimum coST, health, comfort and environmental quality (ReCO_2ST), Horizon 2020 Grant agreement No 748256, www.reco2st.eu

[3] https://www.welt.de/wirtschaft/article169186273/97-neue-Wohntuerme-und-kein-Platz-fuer-Geringverdiener.html, last visited: 27.08.2020

[4] Strey R. 2015. Production of porous materials by the expansion of polymer gels. Patent, WO2015071463A3.

[5] Sankarshan Verma, Harjit Singh, 2020, Vacuum insulation panels for refrigerators, **International Journal of Refrigeration** 112, 215-228.

[6] Singh H., Geisler M. and Menzel F., 2015, Experimental investigations into thermal transport phenomena in vacuum insulation panels (VIPs) using fumed silica cores. **Energy and Buildings** 107, 76–83.

[7] Allgemeine bauaufsichtliche Zulassung Z-23.11-1658, Deutsches Institut für Bautechnik, 10th August 2020

[8] A. Lorenzati, S. Fantucci, A. Capozzoli, M. Perino, 2017, The effect of temperature on thermal performance of fumed silica based Vacuum Insulation Panels for buildings, **Energy Procedia** 111, 490-499.

[9] Jose Tavares, Harjit Singh, Maria Kolokotroni, 2020, Bespoke method for installation of VIPs on building walls and their performance, WORLD RENEWABLE ENERGY CONFERENCE (WREC) Lisbon (Portugal) 2020.