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Replication Studies paper

Cellulosic-crystals as a fumed-silica substitute in vacuum insulated panel technology used in building construction and retrofit applications

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ABSTRACT

This article investigates impact of substituting fumed silica with a cellulosic-crystal innovation in a commercial Vacuum Insulated Panel (VIP) core. High building performance demands have attracted VIP technology investment to increase production capacity and reduce cost. In building retrofit VIPs resolve practical problems on space saving that conventional insulations are unsuitable for. Three challenges exists in fumed silica: *cost*, *low sustainability properties*, and *manufacture technical maturity*. Cellulosic nano-crystal (CNC) technology is in its infancy and was identified as a possible alternative due to a similar physical nano-structure, and biodegradability. The study aim was to determine a *performance starting point* and establish how this compares with the current benchmarks. Laboratory cellulosic-crystal samples were produced and supplied for incorporation into commercial VIP manufacture. A selection of cellulosic-panels with core densities ranging 127–170 kg/m^3 were produced. Thermal conductivities were tested at a pressure of 1 Pa (0.01 mBar), with the results compared against a selection of fumed silica-VIPs with core densities ranging 144–180 kg/m^3. Conductivity tests were then done on a cellulosic-VIP with 140 kg/m^3 density, under variable pressures ranging 1–100,000 Pa (0.01–1000 mBar). This investigated panel lifespan performance, with comparisons made to a fumed silica-VIP of similar core density. Manufactured cellulosic-samples were found unsuitable as a commercial substitute, with performance below current standards. Areas for cellulosic nano-material technology development were identified that show large scope for improvement. Pursuit could create a new generation of insulation materials that resolve problems associated with current commercial versions. This is most applicable in building retrofit where large ranges of domestic and commercial cases are marginalised from their construction markets due to impracticalities and high upgrade costs. This being a problem in multiple economies globally.

1. Introduction

Vacuum insulated panel (VIP) technology permits the specification of low thermal U-value elements in buildings. Research and development has been extensive, with reviews covering these including: Simmler et al. [1], Fricke et al. [2], Baetons et al. [3], Alam et al. [4], Fuchs et al. [5], Johansson [6], Kalnæs and Jelle [7], and Brunner et al. [8]. VIP applications are numerous, with example studies including: building retrofit [9], district heating [10], thermal storage [11], and solar energy [12]. The technology is comprised of a fumed silica based core coated in a sealed evacuated aluminium based film. Rigidity of the centre is maintained using small quantities of micro-fibres for shape retention, combined with infrared opacifier for radiation transfer suppression (Figs. 1 and 2) [13]. Coating films are typically made of polymers, including: Polyethylene Terephthalate [PET], Polyethylene [PE], and Polypropylene [PP], these alternated with metal layers (Al, Steel, AlOx, SiOx) that prevent gas penetration into the core [13–15]. A cross-section of a VIP film envelope is shown in Fig. 3 with typical layer thicknesses [1,13].

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List of variables

λ_r	Radiation conductivity component in insulation (W/m.K)
λ_{ss}	Solid state thermal conductivity in insulation (W/m.K)
λ_g	Gas conductivity component in the pores of the insulation (W/m.K)
λ_{coup}	Coupling effect impact between gas molecules and matrix (W/m.K)
λ_{tot}	Total of all single effects and effective thermal conductivity in VIP application (W/m.K)
λ^0_{gas}	Gas thermal conductivity at ambient pressure (W/m.K)
p_{gas}	Pressure inside the VIP (Pa)
$p_{1/2}$	A material parameter mainly dependent on the pore size of the VIP matrix (Pa)

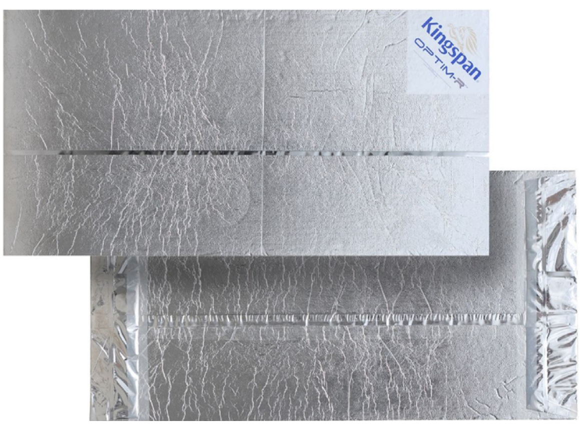


Fig. 1. A standard commercial vacuum insulated panel.

VIP thermal conductivities are five to ten times lower than commercial insulations, with the centre-of-panel reaching 4 mW/m K [3,4,14,16]. Albeit excellent performance, the technology is expensive with panel prices multiples of five to ten that of standard insulations [17,18]. Perspective is given considering space saving provided in a standard solid brick construction aiming for a 0.28 W/m^2 K U-value; where a reduction from 100 mm (mineral fibre or EPS) to 40 mm for VIP can be achieved [3]. In light of cost, the technology is mainly used in niche applications where no alternatives are possible, or where space saving is at a premium [5,10].

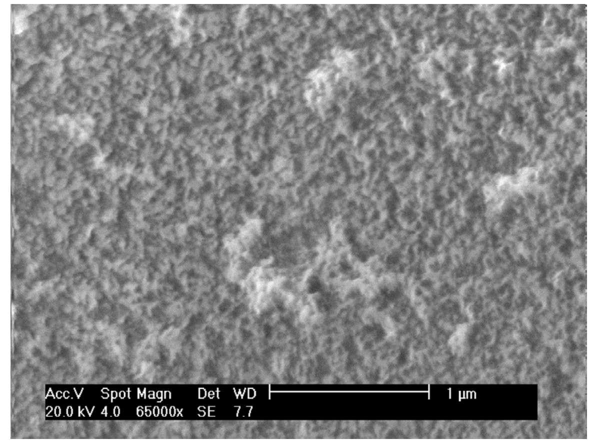


Fig. 2. Macro and microscopic images of the fumed silica based VIP core material.

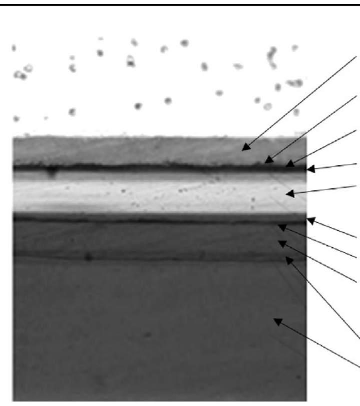
Should a cost-effective solution be developed, it would have massive application in the retrofit field where large groups of buildings cannot be upgraded, due to the impracticality of current commercial insulation systems.

Being the constituent that incorporates the bulk of the VIP embodied energy, recent research advances have focussed on VIP core innovations, including studies by Nemanic et al. [19], Nemanič and Žumer [20], Chen et al. [21], Li et al. [22–24], Chang et al. [25], and Choi et al. [26]. Albeit comprehensive, the focus of these articles leaned towards the physical impacts of fumed silica based core material innovations. The cellulosic innovation was investigated as a fumed silica alternative for VIP cores, this done on the grounds of mitigating the barriers to market mentioned. The content reflects the order of analysis in evaluating the given hypothesis, with sections provided on review of current research, methodology, and results and discussion. The purpose was to establish a starting point for an ongoing body of research, in light of the infancy of nano-cellulose technology. The stakeholders aimed to use outcomes to plan future development paths to enable the substitution concept both technically and economically feasible. The collaborating industrial partner provides multiple insulation system solutions internationally, with its primary business the building industry.

2. Review

2.1. Commercial and super insulation heat transfer

Insulation thermal conductivity is the sum of internal solid-state conductivity, convection, and radiative (infrared) trans-



Layer	Material	Function	Thickness
1	PET	Protecting layer (substrate for 2)	12 µm
2	ALU	Aluminium barrier layer	30 nm
3	PUR	Polyurethane glue layer	2 µm
4	ALU	Aluminium barrier layer	30 nm
5	PP	Polypropylene (substrate for 4)	18 µm
6	PUR	Polyurethane glue layer	2 µm
7	ALU	Aluminium barrier layer	30 nm
8	PET	Polyethylene Terephthalate layer (substrate for 7)	12 µm
9	PUR	Polyurethane glue layer	2 µm
10	PE-LD	Polyethylene sealant layer	60 µm

Fig. 3. Details of film composition [1,13].