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# Development and thermal performance verification of composite insulation boards containing foam-encapsulated vacuum insulation panels☆

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## HIGHLIGHTS

- Developed prototypes of foam-vacuum insulation composite boards in a manufacturing plant.
- Performed laboratory evaluations to test the efficacy of foam encapsulation of vacuum insulation cores.
- Verified thermal resistance of the composite to be at least twice that of current building insulation materials.
- Initiated long-term performance testing of the composite insulation in a real building.

## ARTICLE INFO

*Keywords:*
Vacuum insulation
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Composite foam insulation
Guarded hot box
Natural exposure test

## ABSTRACT

High-performance thermal insulation is a critical need for buildings. This article presents the development and thermal characterization of composite foam insulation boards containing low-cost vacuum insulation cores. The composite foam-vacuum insulation boards were created in a semi-automatic operation in a foam insulation manufacturing plant. The low-cost vacuum insulation is a new technology called modified atmosphere insulation. The production process of modified atmosphere insulation is much simpler than traditional vacuum insulation manufacturing, and it has the potential for significant cost reduction at the same thermal performance. Prototypes of small- and full-scale composite insulation boards were created for testing and evaluation under laboratory and natural weatherization conditions. The laboratory tests showed that the overall thermal resistance of the composite insulation board is at least twice that of current rigid foam insulation used in building envelope. Ongoing test of the composite insulation in a natural exposure test facility indicates that the high thermal performance was retained through handling and installation as well as natural aging over a period of one and a half years.

## 1. Introduction

Buildings account for 40% of the global energy consumption and over 30% of the carbon dioxide emission, with a large fraction of the energy consumption spent on maintaining thermal comfort [1]. Building insulation plays a key role in developing energy efficient buildings by reducing heat losses through the building fabric and, due to their higher thermal resistance, vacuum insulation panels (VIPs) represent a more effective alternative to conventional building insulation materials [2]. Review articles by Alotaibi and Riffat [3] and Kalnæs and Jelle [4], among others, have studied and summarized the state-of-the-art of VIPs, their current limitations and future research opportunities. VIPs typically consist of an open-celled, porous core material which is evacuated and sealed within an impermeable envelope (or barrier film) to maintain the required quality of the vacuum within [5]. In conventional insulation materials like mineral wool, fiberglass or organic foams, the total heat transfer is dominated by the contribution of the non-convective gas, or gas conductivity, within the

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**Nomenclature**

| | |
|---|---|
| *a* | coefficients in conductivity equation |
| *k* | thermal conductivity (W/m K) |
| *M* | mean |
| *P* | internal pressure (mbar) |
| *Q* | solar irradiance ($W/m^2$) |
| *R* | thermal resistance ($m^2$ K/W) |
| *q* | heat flux ($W/m^2$) |
| *T* | temperature (°C or K) |

*Subscripts*

| | |
|---|---|
| *ext* | exterior |
| *int* | interior |
| *o* | outside |
| *s* | solar |

*Abbreviations*

| | |
|---|---|
| CI | continuous insulation |
| EPS | expanded polystyrene |
| GHB | guarded hot box |
| HD | high-density |
| HFM | heat flow meter |
| HFT | heat flux transducer |
| IR | infrared |
| MAI | modified atmosphere insulation |
| NET | natural exposure test |
| NIST | National Institute of Standards and Technology |
| PIR | polyisocyanurate |
| SD | standard deviation |
| SRM | standard reference material |
| VIP | vacuum insulation panel |
| XPS | extruded polystyrene |

hollow spaces or pores of the insulation [5]. Thus, evacuation of the pores to reduce or eliminate the gas conductivity can result in a significantly improved thermal performance, i.e. thermal resistances that are five to ten times better than conventional insulation [5].

The core material is a key component of VIPs as its structure (pore size, porosity, etc.) dictates the quality of vacuum needed to achieve the desired performance and, in turn, the quality of the barrier films needed to maintain the internal vacuum over the application lifetime. Commercial VIPs have used core materials consisting of fumed silica, aerogels, polyurethane foam and glass fiber [4], while new core materials are still being researched, such as phenolic foam [6] and melamine–formaldehyde rigid foam [7]. Researchers have also investigated integration of phase change materials (PCMs) into precipitated silica for VIPs; the outcome was that the thermal mass of PCM-VIPs increased but also the thermal conductivity [8]. Fumed silica has proven to be better than fiber and foam-based core materials as it can achieve a low conductivity of 0.005 W/m K at a relatively high internal pressure of 50 mbar; fiber and foam-based core materials need to be evacuated to 1 mbar or lower to achieve the same conductivity [5]. Alam et al. [9] performed an energy and economic analysis of fumed silica and glass fiber-based VIPs for use as added insulation in non-domestic buildings. Appropriate thicknesses of the fumed silica and glass fiber VIPs were assumed to provide the same thermal resistance. Addition of the VIPs was estimated to reduce heating energy consumption by 10 to 27%, based on building type [9]. However, the fumed silica VIP had shorter payback than the glass fiber VIP. The glass fiber VIPs had an assumed lifetime of 10 years compared to 60 years of the fumed silica VIPs; thus, the glass fiber VIPs would need to be replaced during the building service life, also 60 years, resulting in added investment costs [9].

While center-of-panel (COP) conductivities of fumed-silica VIPs are in the 0.005 W/m K range, the overall conductance of VIP-based composites or systems can be significantly higher due to edge effects, i.e. heat flows along the VIPs edges. The edge effects are influenced by the edge design, barrier film composition (metallic vs. non-metallic), and materials between the joints and adjacent to the VIPs [10]. Sprengard and Holm [11] performed simulations to investigate the thermal bridging effects in VIPs and estimated the equivalent thermal conductivity of the VIPs. The influencing factors considered included edge design, VIP dimensions, and thickness and conductivity of the barrier film. The results showed that for VIPs of dimensions 0.3 m × 0.4 m or smaller, the equivalent conductivity could be more than 10% greater than the COP value; for larger panels the increase in equivalent conductivity ranged from 2.5 to 8% [11].

Nussbaumer et al. [12] studied the application of foam-covered VIPs to concrete walls experimentally and numerically. The VIPs were 40 mm thick and were sandwiched by 10 mm foam layers for protection, resulting in a total thickness of 60 mm. The VIPs lowered the thermal conductance of the uninsulated concrete wall by 95%; in comparison, 212 mm of regular foam insulation would be required for the same reduction in conductance [12]. Grynning et al. [13] reported hot box measurements and simulations of multiple VIP-based walls structures to evaluate the impact of VIP arrangement on their thermal performance. The tested configurations included single and double layers of VIPs, straight and tapered edges, and regular and staggered joints. As expected, thicker VIPs or double-layered VIPs achieved lower thermal conductance compared to single layer VIPs. Staggering the joints and taping the seams between the VIPs yielded marginally lower conductances compared to regular joints and open seams [13].

Mukhopadhyaya et al. [14] reported the demonstration of VIPs in a retrofit application of a concrete wall in a subarctic climate. The VIP-based exterior insulation system consisted of 12 mm thick VIPs sandwiched by 25 mm polystyrene foam board on one side and a combination of 6 mm flexible polyurethane foam and 25 mm polystyrene board on the other. The reason for sandwiching the VIPs within foam boards was to prevent damage via abrasion of the VIPs with adjacent materials. The wall assembly was monitored over three winter periods and no discernible performance degradation in thermal performance of the VIPs was observed [14].

VIP-based composite insulation systems are currently a high-priority research area for the United States (U.S.) Department of Energy's Building Technologies Office (www.energy.gov/eere/buildings/building-technologies-office) [15]. Buildings consume more that 40% of the total primary energy in the U.S., with 14 to 28% of the energy in buildings used for space heating and cooling. Adequately insulating the building enclosure or envelope is one of most effective mitigation measures to reduce the space heating and cooling energy consumption in buildings, especially for older, poorly insulated buildings. Retrofitting older buildings with current insulation materials has proven challenging, hence the interest in novel insulation systems with higher thermal resistivity [15].

This article describes the development and comprehensive structural and thermal characterization of novel composite insulation boards containing VIP cores, which were fully encapsulated by spray-applied closed-cell foam insulation. The foam encapsulation serves to protect the embedded VIPs and extend their service life. The composite board can achieve a thermal resistance of 4.5 $m^2$ K/W at 5.1 cm thickness; in comparison, current foam and fibrous building insulations can only achieve 2.1 $m^2$ K/W or less at the same thickness [16]. This work was motivated by the need to develop insulation systems with higher thermal performance than current building insulation materials.

The vacuum insulation used in these composite boards is called modified atmosphere insulation (MAI) [17] and the encapsulating foam