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Air-Filled Nanopore Based High-Performance Thermal Insulation Materials

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Abstract

State-of-the-art thermal insulation solutions like vacuum insulation panels (VIP) and aerogels have low thermal conductivity, but their drawbacks may make them unable to be the thermal insulation solutions that will revolutionize the building industry regarding energy-efficient building envelopes. Nevertheless, learning from these materials may be crucial to make new and novel high-performance thermal insulation products. This study presents a review on the state-of-the-art air-filled thermal insulation materials for building purposes, with respect to both commercial and novel laboratory developments. VIP, even if today's solutions require a core with vacuum in the pores, are also treated briefly, as they bear the promise of developing high-performance thermal insulation materials without the need of vacuum. In addition, possible pathways for taking the step from today´s solutions to new ones for the future using existing knowledge and research are discussed. A special focus is made on the possible utilization of the Knudsen effect in air-filled nanopore thermal insulation materials.

Keywords: High-performance thermal insulation; Nano insulation material; NIM; Aerogel; Vacuum insulation panel; VIP.

1. Introduction

Immediate priorities and future goals will need to reflect the enhanced energy efficiency options combined with a decarbonized power sector that may reduce the CO_2 emission in the building sector. However, given constraints on

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resources there is a call to focus more on efficient building envelopes to keep energy use down. The building envelope determines the amount of energy needed to heat and cool a building, and hence needs to be optimized to keep heating and cooling loads to a minimum. The importance of heating and cooling in total building energy use is very diverse with this share varying between 20% and 80%. Thus, thermal insulation with significantly lower thermal conductivity may contribute largely to an increased thermal resistance and hence an overall reduced energy consumption in buildings.

This study starts with giving an overview of the theoretical background of the process of heat conduction in thermal insulation materials applied in building envelopes, which helps developing an understanding of how such materials behave when used to achieve improved insulation properties. Furthermore, the study demonstrates the theoretical principle by utilizing the Knudsen effect for reduced thermal gas conductance in nanopores that has considerable impact on the overall thermal conductivity.

Secondly, this study presents the state-of-the-art solutions for building purposes, e.g. aerogels and vacuum insulation panels, discussing both benefits and drawbacks. The solutions are investigated with respect to both commercially available products and the global research front, and all property values are retrieved from sources late 2016. The final part will offer some recommendations and ideas on the direction in which the development could proceed, providing a pathway to further advance towards the goal of achieving the improved thermal insulation materials of tomorrow with a substantially lowered thermal conductivity value utilizing the Knudsen effect.

2. Heat transfer in materials

All materials have specific properties when it comes to conduction of heat, and this is irrespective to whether one are looking at solids, liquids or gases. Heat flows spontaneously from a higher temperature body to a lower temperature body, and this will happen as a result of solid state and gas conduction, radiation and convection [1]. The relation between the different contributions are often described as in the following [2]:

$$\lambda_{total} = \lambda_{solid} + \lambda_{gas} + \lambda_{rad} + \lambda_{conv} + \lambda_{coup} + \lambda_{leak} \tag{1}$$

where λ_{solid} is solid state conductivity, λ_{gas} is gas conductivity, λ_{rad} is radiation conductivity, λ_{conv} is convection conductivity, λ_{coup} is conductivity due to coupling effects between the other terms in Eq.1, and λ_{leak} is (air) leakage thermal conductivity.

In addition, it is important to identify which of the terms contribute most to the thermal transport. As we will see later for vacuum insulation panels (VIP), the gas conduction part is very large and the most dominant when the VIP is punctured.

3. The Knudsen effect

Conventional thermal insulation materials are produced so the effects of conduction, radiation and convection are minimized. Using low-radiative surfaces and porous structures reduces radiation, convection and solid conduction, but due to the size of the pores and the open-porous material, the gaseous thermal conduction is limited to the conductivity of air [3]. A solution to this is to utilize the Knudsen effect. This effect is explained by the equations in the following, and implies that a reduction of the pore size in the material to the nano range will effectively reduce the thermal conductivity [4]:

$$\lambda_{gas} = \frac{\lambda_{gas,0}}{1+2\beta Kn} \tag{2}$$

where

$$Kn = \frac{\sigma_{mean}}{\delta} = \frac{k_B T}{\sqrt{2}\pi d^2 p \delta} \tag{3}$$

where λ_{gas} is a combination of thermal conductivity of the gas inside the pores on nanoscale and the energy transfer when molecules collide with pore walls (the latter from the β factor), $\lambda_{gas,0}$ is the thermal conductivity for air at standard