Comparison of Different Insulating Materials

ME-16-02 Heat Transfer - Abedian

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Description

In this project we will be comparing the performance of different insulating materials in the context of tiny-houses, small living spaces typically smaller than 400 ft^2. In these small houses, the lower cost of living is associated with substandard utilities – leading to question how effectively one could retain warmth during a New England winter. In our analysis we'll be determining the time it takes for aerogel insulation vs. conventional fiberglass insulation to cool down to a minimal temperature. This insight into the effectiveness of retaining heat can help inform the long term cost of utilities in these small homes.

Motivation

If we take a snapshot of the problems faced by young adults in America, the current housing crisis stands as one of the most frequently discussed. Let it be clear that housing should be a universal right extended to even the most vulnerable members of our society. Due to rapid urbanization and the rising cost of living in major cities across the US, many people have sought solutions including the building of shelters, high-rise skyscrapers, and the repurposing of older buildings. If the trends of rapid urbanization continue, however, this may become a fruitless effort. Another possible solution could be rooted in the tiny-house movement.

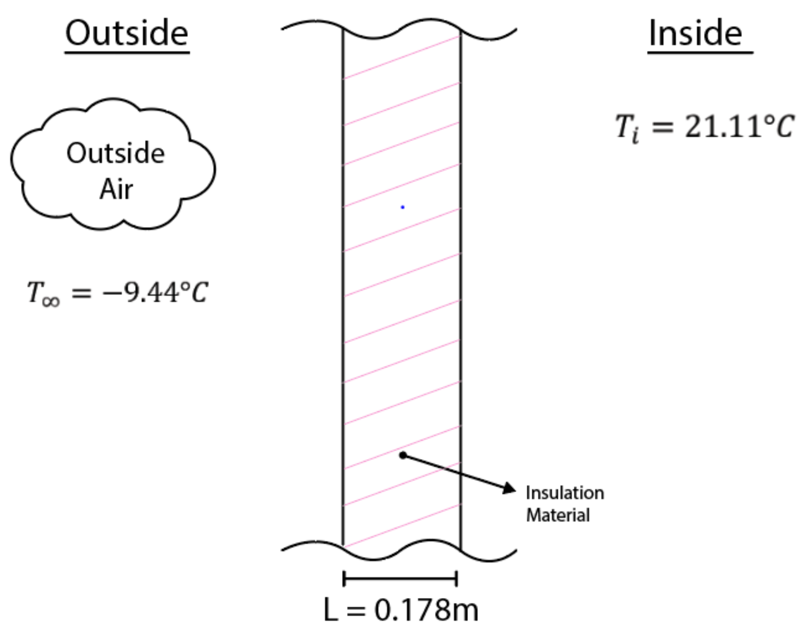
We wanted to explore the family of Aerogels as a space-saving form of insulation. In the 20^{th} century, the novel aerogels were used in industrial applications as insulation for tubing and pipelines. Aerogels, a silica-based polymer compound, are revered for their remarkable heat capacity and density. These properties make it possible to achieve a similar performance for insulation when there is a concern for tight spaces. We want to explore a comparison of traditional insulation material (fiberglass) vs. aerogel as an insulator. Since Aerogels are purported as excellent insulators (R-value = 1.76 $\frac{m{*}K}{W}$), we want to prove its capabilities in a simplified model during a New England winter. Namely, we want to compare performance with typical insulation material. We hope that this will be presented in a format that encourages future exploration and expansion in the applications of aerogels.

Concepts

In this analysis and comparison, we use the concept of conduction. Conduction being the transfer of heat between substances or objects that are in direct contact with each other. More specifically, we will be looking at how conduction works over time and the spacial effects. By using the Biot number along with the Fourier number we will be able to relate the temperature difference and the max temperature difference with the time it takes for that difference to occur. We will be using these equations to relate these variables:

$$\theta^* = \frac{\theta}{\theta_i} = \frac{T - T_\infty}{T_i - T_\infty} \qquad t^* = \frac{\alpha t}{L^2} = Fo \qquad \theta^* = C_1 exp(-\zeta_1^2 Fo) \qquad \alpha = \frac{k}{\rho C_p}$$

Diagram



In this problem, we are assuming this is a room that is in an area where the temperature outside gets very cold. To simplify our calculations, we are also assuming that the walls that enclose the insulation have no effect on the conduction analysis. Because both walls in both scenarios would be made of the same material and same thickness, they should have the same impact with both insulations. The length, L, for both insulation materials will also stay the same. We are also assuming 1-D conduction in the X-direction, assuming negligible radiation effects, and assuming constant properties throughout the material.

Calculations

Defining Constants & Material Properties

$T_{inf} := 263.71\ \boldsymbol{K}$ $\quad T_i := 294.76\ \boldsymbol{K}$ $\quad T := 288.71\ \boldsymbol{K}$ $\quad h_{air} := 10\ \dfrac{\boldsymbol{W}}{\boldsymbol{m}^2 \cdot \boldsymbol{K}}$

Material 1: Fiberglass Insulation

$\rho_1 := 20\ \dfrac{\boldsymbol{kg}}{\boldsymbol{m}^3}$ $\quad k_1 := 0.046\ \dfrac{\boldsymbol{W}}{\boldsymbol{m} \cdot \boldsymbol{K}}$ $\quad L_1 := 0.178\ \boldsymbol{m}$ $\quad C_{p1} := 1030\ \dfrac{\boldsymbol{J}}{\boldsymbol{kg} \cdot \boldsymbol{K}}$

Material 2: Aerogel Insulation

$\rho_2 := 71.23\ \dfrac{\boldsymbol{kg}}{\boldsymbol{m}^3}$ $\quad k_2 := 0.006\ \dfrac{\boldsymbol{W}}{\boldsymbol{m} \cdot \boldsymbol{K}}$ $\quad L_2 := 0.178\ \boldsymbol{m}$ $\quad C_{p2} := 1150\ \dfrac{\boldsymbol{J}}{\boldsymbol{kg} \cdot \boldsymbol{K}}$

Key Equations

$Bi := \dfrac{h \cdot L}{k}$ $\quad \theta_o := \dfrac{T - T_{inf}}{T_i - T_{inf}}$ $\quad \theta_o := C_1 \cdot e^{\left(-\zeta_1{}^2 \cdot Fo\right)}$ $\quad t_1 := \dfrac{\alpha \cdot t}{L^2}$

Cool Down Time Calculation (Material 1)

$\alpha_1 := \dfrac{k_1}{\rho_1 \cdot C_{p1}} = \left(2.233 \cdot 10^{-6}\right)\ \dfrac{\boldsymbol{m}^2}{\boldsymbol{s}}$ $\quad \theta_{o1} := \dfrac{T - T_{inf}}{T_i - T_{inf}} = 0.805$

$Bi_1 := \dfrac{h_{air} \cdot L_1}{k_1} = 38.696 >> 0.1$ Use One Term Approximation

Table 5.1 $\quad \zeta_1 := 1.5325\ \boldsymbol{rad}$ $\quad C_1 := 1.2723$

$Fo_1 := \dfrac{\alpha \cdot t}{L_1{}^2}$

$Fo_1 := \text{abs}\left(\ln\left(\dfrac{\theta_{o1}}{C_1}\right)\right) \cdot \dfrac{1}{\zeta_1{}^2} = 0.195$ $\quad t := \dfrac{\left(Fo_1\right) \cdot L_1{}^2}{\alpha_1} = 0.768\ \boldsymbol{hr}$

Cool Down Time Calculation (Material 2: Aerogel Insulation)

$$\alpha_2 := \frac{k_2}{\rho_2 \cdot C_{p2}} = \left(7.325 \cdot 10^{-8}\right) \frac{m^2}{s} \qquad \theta_{o2} := \frac{T - T_{inf}}{T_i - T_{inf}} = 0.805$$

$$Bi_2 := \frac{h_{air} \cdot L_2}{k_2} = 296.667$$ >>0.1 Use One Term Approximation

Table 5.1 (Biot number at infinity) $\zeta_2 := 1.5708\ rad$ $C_2 := 1.2733$

$$Fo_2 := \text{abs}\left(\ln\left(\frac{\theta_{o2}}{C_2}\right)\right) \cdot \frac{1}{\zeta_2^{\,2}} = 0.186 \qquad t := \frac{\left(Fo_2\right) \cdot L_2^{\,2}}{\alpha_2} = 22.32\ hr$$

Results

Using the different thermal properties for Aerogel and for standard house insulation, we were able to obtain a significant difference in how long it would take for a room to cool down from 70 degrees fahrenheit to 60 degrees fahrenheit. Our results show that for a room with standard fiberglass insulation to go from 70˚F to 60˚F with an outside temperature of 15˚F it will take 0.768 hours. While an Aerogel insulation with the same parameters will take 22.32 hours to warm up from 70˚F to 60˚F. Our calculations prove that aerogels are a better insulator than standard fiberglass insulation, it takes over 20 times more time for the temperature to fall to 60˚F. This means that the heater in a house would have to do much less work during the winter, therefore save house owners a lot more money in gas bills. Aside from this, it also means that an owner of a tiny-house, could use a lot less material for insulation, therefore reducing their carbon footprint.

References

Sachithanadam, M. (n.d.). Silica Aerogel Composites: Novel Fabrication Methods (pp. 5–49).

Woods, T. (n.d.). Aerogels: Thinner, Lighter, Stronger. NASA. Retrieved December 16, 2019, from https://www.nasa.gov/topics/technology/features/aerogels.html

Gurav, J. L., Jung, I.-K., Park, H.-H., Kang, E. S., & Nadargi, D. Y. (2010). Silica Aerogel: Synthesis and Applications. Journal of Nanomaterials, 2010, 1–11. Retrieved December 16, 2019, from 10.1155/2010/409310

"Chapter 5." *Fundamentals of Heat and Mass Transfer*, by Frank P. Incropera, J. Wiley, 2007, pp. 270–275.