Thermal Conductivity and Specific Heat Capacity of Insulation materials at Different Mean Temperatures

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Abstract. Thermal conductivity and heat capacity are among the most essential properties of a building insulation in calculating thermal performance which are subjected to change when exposed to temperatures variation in service. Ignoring the temperature dependency of these material properties can result in under and over estimations of buildings energy uses and the corresponding equipment sizing. To obtain more realistic conductivity values of insulation materials, in this paper, thermal conductivity tests are conducted at various mean temperatures. For the study six commonly used insulations including Cellulose fiber, Expanded Polystyrene, Extruded Polystyrene, Open Cell Spray Polyurethane, Polyisocyanurate, and Mineral Wool are considered, and their thermal conductivity are measured at seven mean temperatures ranging from 5°C to 60°C. Furthermore, their specific heat capacity are measured at nine mean temperatures ranging between 16°C and 36°C. The results showed that except Polyisocyanurate board, the thermal conductivities and specific heat capacities of all insulation materials increased linearly with rising temperature, presenting a linear regression model with correlation coefficients ($R^2$) values between 0.96 and 0.98. The curve fitting of the Polyisocyanurate thermal conductivity measurements resulted a nonlinear regression model with $R^2$ of 0.97. The thermal conductivity of six insulations as a function of temperature have been established.

1. Introduction

Buildings account for nearly 40% of the global energy consumption [1] of which 85 to 95% is for building operations [2]. Using building envelopes with efficient thermal performance help to prevent heat flux with the surrounding through the envelope and conserves energy. Consequently, less operational energy is required for space cooling in summer and heating in winter [3]. Therefore, the application of insulation in building envelopes is considered as a simple yet highly energy efficient approach that can be used to residential, commercial and industrial sectors [4]. The thermal performance of a building envelope is governed by the thermal properties of its constituent materials including the heat capacity and the thermal conductivity. The thermal conductivity of a material at a point is defined as the ratio between the density of heat flow rate and the magnitude of the thermal gradient in the direction of the flow while the specific heat capacity determines how much heat energy is absorbed or released depending on the temperature difference and mass. Building envelopes are exposed to extreme temperature regimes, worldwide, ranging from -50°C to +50°C which causes the temperature of the roofs and walls to reach over 80°C in summer and below 0°C in winter. Local temperature fluctuations, among several other factors including moisture content, density, pore fraction and distribution, and age, significantly affects thermal conductivity [5-7].
Although several research organizations have been determining the thermal conductivity of building materials, however, insulation materials are continuously evolving due to the evolution and variation of the manufacturing processes through the time and among different manufacturers of the same product. Therefore, it is compelling to determine the changes in insulation materials’ properties at least once in a decade. This will ensure that the hygrothermal models are using valid database and functional dependencies for the properties of each material.

1.1. Temperature Dependency
The influence of operating temperature on the thermal conductivity of insulation materials has been the subject of several numerical and experimental studies [8, 9], which all agreed upon increasing the thermal conductivity with rising temperature. Bomberg and Klarsfeld [10] studied the impact of mean temperature variation on the thermal conductivity of mineral fiber insulation. The study analysis revealed that the thermal conductivity in mineral fiber insulation increased at higher temperatures. Investigating the thermal performance of highly porous fibrous insulations, Karamanos, Hadriarakou [5] and Daryabeigi, Cunnington [11] highlighted radiation and gas conduction as the primary components affecting the heat transfer in fibrous insulation which both increase with temperature, whereas, conduction through the solid has the lowest impact on heat transfer. Since, the radiation properties vary with wave length, the radiation component can be expected to change considerably with the increase in temperature difference [9]. This phenomenon is one of the factors which causes the thermal conductivity in low density materials to be more sensitive to temperature difference.

In multiple research, Abdou and Budaiwi studied the thermal performance of 32 different locally manufactured insulation materials from seven categories namely, fiberglass, wood wool, rock wool, mineral wool, polyethylene, polyurethane and polystyrene [12]. The insulation materials were tested within a wall assembly at five different mean temperatures including 4°C, 10°C, 24°C, 38°C, and 43°C. They concluded that the thermal conductivities of all insulation materials rose upon increasing the operating temperature. The thermal conductivity of polyethylene and polystyrene insulations presented maximum and minimum increases with temperature, respectively [12]. Using the transient plane source (TPS) technique, Al-Ajlan [13] also investigated temperature dependency of thermal conductivity of the same categories of local insulations as [12] at mean temperatures of 22°C, 35°C, 50°C and 65°C. According to this study, the thermal conductivity increased with temperature, where the increase was more significant at temperatures lower than 35°C. The results showed that the thermal conductivity of polyurethane insulation was more temperature sensitive than polystyrene insulation. Koru [14] studied the temperature dependency along with the impact of density on thermal conductivity of closed-cell insulation materials including: expanded polystyrene (EPS), extruded polystyrene (XPS), expanded nitril rubber (ENR), polyurethane (PUR), polyethylene (PE). Measurements were carried out at fourteen different mean temperatures from −10°C to +55°C with 5°C steps and ΔT of 20°C. The results indicated increase in thermal conductivity with rising temperature and decrease with increasing density of tested materials. He explained that the volume of air in the structure increases upon rising temperature which intensifies the kinetic energy levels of the molecules.

Considering the dependency of thermal conductivity of materials on local temperature fluctuations, it is important to conduct the tests while material samples are exposed to real or similar environmental conditions to obtain reliable values. However, currently, values for material properties at academic and manufacturer laboratories often measured following the standard test methods which suggest conditions within a limited range of temperature and relative humidity, such as 21°C - 23°C and 50% - 75% RH [15]. For decades, few research organizations systematically determine the thermal conductivity of insulation materials. However, thermal insulations are continually evolving due to technological improvements and variations in the production processes among different manufacturers of the same product. Therefore, the published values for material properties are usually not sufficient for accurate calculations as they become outdated after a while given those ongoing changes [16]. In this research project, we aimed to study the
temperature dependency of thermal conductivity and specific heat capacity of commonly used insulation materials at extended mean temperatures below and above the current standard conditions.

2. Materials and Methods

In this research, various types of insulating materials have been selected to investigate a wide range of commercially available insulation materials for buildings. Therefore, samples of expanded polystyrene insulation (EPS), extruded polystyrene insulation (XPS), polyisocyanurate insulated sheathing board (Polyiso), and mineral fiber (Stone Wool) were provided from local stores. Additionally, cellulose fiber insulation samples are taken from a commercial cellulose insulation product blown according to the manufacturer’s directions. The product is prepared from recycled newspaper as the base material using a dry fiberization technology. The fire retardant and fungicide are also applied as dry raw materials during the production process. Furthermore, open cell sprayed polyurethane specimens are provided using a commercial product commonly known as half-pound SPF.

2.1. Experimental Measurement and Equipment

The thermal conductivities of building products were determined using the heat flow meter (HFM) Lambda 2000 apparatus following the instruction described in ASTM standard C518-04 [15]. The HFM apparatus establishes a steady state one-dimensional heat flux through a test specimen at constant but different temperatures. Thermal conductivity is determined, upon achieving thermal equilibrium and uniform temperature gradient throughout the sample. The general principle of the HFM is based on the Fourier’s law of heat conduction as the Equation 1 that governs the rate of heat flow [17]:

\[ q = \lambda \frac{\Delta T}{L} \]  

(1)

Where \( q \) [W/m²] is the density of heat transfer, \( \lambda \) [W/(m.K)] is the thermal conductivity of the material sample and \( \Delta T \) [K] is the temperature difference. Since the heat flow meter apparatus is a comparative or secondary method of measurement, thus, before starting measurements, the heat flow meter was calibrated using the Standard Reference Material (SRM) 1450c at designated temperatures in accordance with ASTM-C518 [15]. The reference sample was tested 6 times at 24°C over an extended period of time to ensure accuracy and repeatability. Accordingly, the calibration factor (coefficient) was calculated for each designated mean temperature using heat flux transducers outputs from both plates of the HFM.

The specific heat capacity of the tested materials was measured using the LaserComp Fox 600 HFM which has an ability to measure the thermal conductivity of materials in the range between 0.005 to 0.35 W/m.K with accuracy and temperature control of ±1 % and ±0.01°C, respectively. Its working area range is 610 mm × 610 mm and a maximum tested thickness of 203 mm. Upon calibrating the HFM using NIST SRM 1450b, measurement method followed ASTM-C1784-14 [18] which is based on the principle of calculating the amount of absorbed total heat energy \( H_{total} \) (J/m²) by the specimen from the HFM outputs. In order to calculate the volumetric specific heat capacity \( C_p \rho \) (J/m³.K) of materials, the apparatus is pre-programmed to calculate \( H_{HFMS} \) \( (C_p \rho \cdot 2 \delta x) \) using transducers heat capacity coefficients by the manufacturer and automatically subtracted it from \( H_{total} \) using the Equation 2 [19]:

\[ C_p \rho = \left( \frac{H_{total}}{\Delta T} - H_{HFMS} \right) / x \]  

(2)

2.2. Specimens Preparation and Test Conditions

Four square-shape samples of each tested insulation materials with a dimension of 300 × 300 mm were cut preferably with maintaining the original thickness of insulations products. The selected samples were kept at normal lab conditions for an adequate period of time (at least six months) before test to meet the testing method instruction. It was necessary to smooth the surfaces of sprayed foam polyurethane and cellulose fiber samples to achieve uniform plate-to-specimen thermal contact, Figure 1. Therefore, rough and uneven surfaces of those insulation samples were removed while maintaining adequate thickness for the test.
Figure 1. Spray polyurethane insulation: (a) sprayed samples with rough and uneven surface, (b) prepared specimen with smooth surface.

Thermal conductivity as a function of temperature is an empirical relationship based on experimental data. Therefore, it is essential that a range of temperature suitable to the material should be employed in order to determine the function, $\lambda(t)$ [9]. In an appropriate range of temperature, it is important to perform tests at enough mean temperatures. Thus, in this study, the thermal conductivity of each selected sample was measured at seven different mean temperatures: 5°C, 10°C, 21°C, 24°C, 35°C, 50°C and 60°C with temperature difference of 20°C.

For measuring specific heat capacity, however, larger samples with dimension of 600 mm × 600 mm were prepared following the same procedure as for thermal conductivity measurement. In this study, the set points for heat capacity measurements were selected as 16°C, 18°C, 20°C, 22°C, 24°C, 26°C, 28°C, 30°C and 36°C with steps of 2°C and 6°C. The time for each measurement, to reach the steady state of full thermal equilibrium, varied depending on the size of temperature step, thermal diffusivity of the specimen, material thickness and the amount of energy that was stored in insulation sample. By selecting 2°C steps, it took 4-5h for each temperature set.

3. Results and Discussions

During testing at lower mean temperatures, in some cases condensation and frost build up around the cooling bath pipe are observed due to the higher lab air dew point compared to the pipes surface temperature. In these cases, the experimental runs are terminated and thus no results for those cases not reported here. The results of thermal conductivity and specific heat capacity tests of insulation materials at designated temperatures were plotted against temperature in separate graphs. Additionally, basic physical properties of tested insulations and a summary of their thermal conductivity results along with the results of the least square regression analysis for each tested insulation material are tabulated in Table 1.

As shown in Figure 2-a, the thermal conductivity of cellulose fiber, EPS, XPS, open cell sprayed polyurethane and mineral fiber insulation samples increases upon rising mean temperature. According to the results presented in Table 1, as the mean temperature changes from 5°C to 60°C, the thermal conductivity of open cell sprayed polyurethane foam and cellulose fiber insulation increases by 29.2% and 18.5%, showing the most and least sensitivity to the temperature changes. With the same temperature raise, the thermal conductivity of EPS, XPS, Polyiso and mineral fiber increased by 20%, 23%, 21% and 20%, respectively. These results show the degree of variation that temperature can have an impact on insulations thermal conductivity which cannot be disregarded. Except for Polyiso, the curve fitting of the measurement points yielded a linear regression model with correlation coefficients ($R^2$) values between 0.96 and 0.98.

However, unlike the other insulation materials, the thermal conductivity test for Polyiso insulation board at different mean temperatures showed a nonlinear trend with rising temperature, Figure 2-b. The thermal conductivity in all four Polyiso samples reached to its lowest point at 21°C while increased at other tested mean temperatures. Berardi and Naldi [20] explained that this nonlinear behavior of thermal conductivity
is due to the effect of the blowing agent inside the microstructure of Polyiso. At lower temperatures, it starts condensing which causes the increase of thermal conductivity. The thermal conductivity of the materials as a function of temperature for Polyiso is shown in Figure 2-b and the regression coefficients for the other five insulation materials are provided in Table 1. A small discrepancy was found between the measured thermal conductivity values in this study compared with the corresponding results reported in ASHRAE RP-1018 [21] and IEA-Annex 24 [22], which reflects differences in the physical properties between tested insulations in both projects due to the variations and evolution of manufacturing processes.

![Figure 2](image-url)

Figure 2. a: Measured thermal conductivity vs mean temperature for insulations; b: Measured thermal conductivity vs mean temperature for Polyiso insulation.

Table 1. Summary of Thermal Conductivity results of the insulation materials.

| Material                        | Density (kg/m³) | Thickness (mm) | Thermal conductivity within the measurement range (T_m = 5°C – 60°C) | Least Square Regression Analysis y = ax + b |
|---------------------------------|-----------------|----------------|---------------------------------------------------------------|--------------------------------------------|
|                                 |                 |                | T_m = 5°C T_m = 60°C Thermal conductivity increase (%) | a              | b              | R²               |
| Cellulose Fiber                 | 57              | 48.7           | 0.038 0.045 18.5                                             | 0.0012 | 0.0368         | 0.973            |
| Expanded Polystyrene (EPS)      | 21              | 24.5           | 0.033 0.040 20.9                                            | 0.0012 | 0.0314         | 0.974            |
| Extruded Polystyrene (XPS)      | 25              | 25.5           | 0.028 0.035 23.6                                            | 0.0011 | 0.0268         | 0.971            |
| Open Cell Spray polyurethane    | 14              | 41.5           | 0.035 0.045 29.2                                            | 0.0017 | 0.0322         | 0.969            |
| Mineral Fiber (Stone Wool)      | 127             | 39.5           | 0.032 0.038 19.9                                            | 0.0011 | 0.0307         | 0.961            |

According to the Figure 3-a, the measured specific heat capacity of all tested insulations presented linear upward trend by rising temperature. Upon increasing mean temperature from 16°C to 36°C, the maximum overall raise in heat capacity was observed for cellulose fiber samples as 11%, while the minimum increase
was noted to be less than 1% for EPS and XPS insulation boards. However, compared to other insulation materials, cellulose fiber and mineral fiber showed less fluctuation in measured heat capacity through different mean temperatures. In contrast, the results of specific heat capacity of Polyiso insulation board reflected nonlinear relationship with rising temperature, Figure 3-b. Both ASHRAE RP-1018 and IEA-Annex 24 presented single values for specific heat capacity of building materials measured at 20°C, thus comparison was not applicable and not reported here.

Figure 3. a: Measured heat capacity vs mean temperature for insulation materials; b: Measured heat capacity of Polyiso insulation board vs mean temperature.

4. Conclusion
In this study, the impact of mean temperature on thermal conductivity and heat capacity of six different insulation materials were investigated. Thermal conductivities and heat capacities were measured at different operating temperatures using heat flow meter apparatus. Analyzing the results showed that, except Polyiso insulation board, the thermal conductivities and specific heat capacities of all other cases increased linearly with rising temperature, where the curve fitting of their thermal conductivity measurement points yielded a linear regression model with correlation coefficients ($R^2$) values higher than 0.96. For Polyiso, however, the curve fitting of the thermal conductivity measurements resulted a nonlinear regression model with $R^2$ of 0.97. The small discrepancy between our results and published literature such as ASHRAE RP-1018 [21] highlights the importance of frequent measurement of thermal conductivity of insulation materials to obtain up-to-date values. Insulation materials are often advertised with a fixed thermal conductivity value which is usually measured at 21°C - 23°C. Therefore, using a constant value for conductivity of insulating materials leads overestimated or underestimated heat flux in building envelopes through different seasons exposing different climatic conditions [20]. Considering linear thermal conductivity for insulations allows more realistic heat flow calculation through the building envelope since their conductivity in most cases increase and decrease at higher and lower temperatures, respectively. This study presented thermal conductivity of six insulating materials commonly used in construction in North America as a function of temperature, which can help to increase accuracy of hygrothermal and energy simulations models. However, given the impact of moisture on thermal conductivity and the sensitivity of testing moistened insulation materials, authors believe that more experimental research are required to determine the thermal conductivity of different insulations with various moisture contents at more extreme temperatures.
References

[1] DOE. 2014 Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies, in Energy Efficiency & Renewable Energy, US Department of Energy: Washington, DC.

[2] Thormark, C, 2006. “The effect of material choice on the total energy need and recycling potential of a building”. Building and environment, 41(8): p. 1019-26.

[3] Xu, X, Y Zhang, K Lin, H Di and R Yang, 2005. “Modeling and simulation on the thermal performance of shape-stabilized phase change material floor used in passive solar buildings”. Energy and Buildings, 37(10): p. 1084-91.

[4] Aditya, L, T M I Mahlia, B Rismanchi and H M Ng, M H Hasan, H S C Metselaar, O Muraza and H B Aditiya, 2017. “A review on insulation materials for energy conservation in buildings”. Renewable and sustainable energy reviews, 73: p. 1352-65.

[5] Karamanos, A, S Hadiarakou, and A M Papadopoulos, 2008. “The impact of temperature and moisture on the thermal performance of stone wool”. Energy and Buildings, 40(8): p. 1402-11.

[6] Budaiwi, I, A Abdou, and M Al-Homoud, 2002. “Variations of Thermal Conductivity of Insulation Materials Under Different Operating Temperatures: Impact on Envelope-Induced Cooling Load”. Journal of Architectural Engineering, 8(4): p. 125-32.

[7] Ochs, F, W Heidemann, and H Müller-Steinhagen, 2008. “Effective thermal conductivity of moistened insulation materials as a function of temperature”. International Journal of Heat and Mass Transfer, 51(3): p. 539-52.

[8] Aldrich, D and R Bond, 1985. Thermal performance of rigid cellular foam insulation at subfreezing temperatures. in Thermal Performance of the Exterior Envelopes of Buildings III. ASHRAE/DOE/BTECC Conference.

[9] Peavy, B A, 1996. “A Heat Transfer Note on Temperature Dependent Thermal Conductivity”. Journal of Thermal Insulation and Building Envelopes, 20(1): p. 76-90.

[10] Bomberg, M and S Klarsfeld, 1983. “Semi-empirical model of heat transfer in dry mineral fiber insulations”. Journal of Building Physics, 6(3): p. 156-73.

[11] Daryabeigi, K, G R Cunnington, and J R Knutson, 2011. “Combined heat transfer in high-porosity high-temperature fibrous insulation: Theory and experimental validation”. Journal of thermophysics and heat transfer, 25(4): p. 536-46.

[12] Abdou, A A and I M Budaiwi, 2005. “Comparison of thermal conductivity measurements of building insulation materials under various operating temperatures”. Journal of Building Physics, 29(2): p. 171-84.

[13] Al-Ajlan, S A, 2006. “Measurements of thermal properties of insulation materials by using transient plane source technique”. Applied Thermal Engineering, 26(17–18): p. 2184-91.

[14] Koru, M, 2016. “Determination of Thermal Conductivity of Closed-Cell Insulation Materials That Depend on Temperature and Density”. Arabian Journal for Science and Engineering, 41(11): p. 4337-46.

[15] ASTM-C518. 2010 Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus, in American Society for Testing and Materials, ASTM International: West Conshohocken, PA.

[16] Ruuska, T, J Vinha, and H Kivioja, 2017. “Measuring thermal conductivity and specific heat capacity values of inhomogeneous materials with a heat flow meter apparatus”. Journal of Building Engineering, 9: p. 135-41.
[17] Yener, Y, C P Naveira-Cotta, and S Kakac, 2018 *Heat Conduction, Fifth Edition*. 1 ed. Milton: CRC Press.

[18] ASTM-C1784-14. 2014 Standard Test Method for Using a Heat Flow Meter Apparatus for Measuring Thermal Storage Properties of Phase Change Materials and Products, in *American Society for Testing and Materials*, ASTM International: West Conshohocken, PA.

[19] LaserComp, I, 2007 *Measurements of the Volumetric Specific Heat Cp and Enthalpy of the Phase-Change Materials (PCM) Using the FOX Heat Flow Meter Instruments, AN-PCM LaserComp, Inc.*

[20] Berardi, U and M Naldi, 2017. “The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance”. *Energy & Buildings*, 144: p. 262-75.

[21] Kumaran, M K 2002 A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials, in *Final Report from ASHRAE Research Project RP-1018*, NRC.

[22] Kumaran, M K 1996 IEA Annex 24, Heat Air and Moisture Transfer Through New and Retrofitted Insulated Envelope Parts (Hamtie): Task 3, Material Properties, Final Report, Katholieke Universiteit Leuven.