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TECHNICAL NOTE

Comparison of Thermal Conductivity Measurements of Building Insulation Materials under Various Operating Temperatures

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ABSTRACT: In harsh climates, utilizing thermal insulation in the building envelope can substantially reduce the building thermal load and consequently its energy consumption. The performance of the thermal insulation material is mainly determined by its thermal conductivity (k), which is dependent on the material's density, porosity, moisture content, and mean temperature difference. In practice, the k-value is normally evaluated at 24°C (i.e., k_{24}) according to relevant ASTM standards. However, when placed in the building envelope, thermal insulation materials can be exposed to significant ambient temperature and humidity variations depending on the prevailing climatic conditions. The objective of this study is to assess and compare the effect of operating temperatures on the k-value of various insulation materials commonly used in the building envelope. The k-values for seven categories of insulation materials (i.e., fiberglass, wood wool, mineral wool, rock wool, polyethylene, polyurethane, and polystyrene) are measured at different mean temperatures using an automated heat flow meter. Some preliminary measurements are reported for the purpose of assessing the impact of k-value variation on envelope-induced cooling loads (Budaiwi et al. 2002). In this study, comprehensive measurements, comparison, and analyses of results are presented and discussed. These underline the k-value degree of sensitivity ($(\Delta k/\Delta C)/k_{24}$) of various insulation materials with rising operating temperature. This would allow designers to better evaluate the thermal performance of building envelopes leading to a more realistic thermal assessment and energy requirements of buildings.

KEY WORDS: thermal insulation materials, thermal conductivity, measurements, operating temperature.

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INTRODUCTION

In harsh climates, utilizing thermal insulation in the building envelope can substantially reduce the building thermal load and consequently its energy consumption. Nowadays people are becoming more appreciative of the need to conserve energy mainly due to increased awareness and increased electric energy tariffs. As energy becomes more precious and demand increases, the use of thermal insulation in buildings is being enforced in new building constructions. Many parameters should be considered when selecting thermal insulation, including cost, compression strength, water vapor absorption and transmission and, most importantly, the thermal conductivity (k) of the material. The k of insulation materials is the most important property that is of interest when considering thermal performance and energy conservation measures. ASTM standards C168-97 [2] define thermal conductivity (k-value, W/m K) as the time rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area.

Insulation materials can be made in different forms including loose-fill form, batt or blanket form, rigid form, foamed in place, or reflective form. The choice of the proper insulation material form and type depends on the type of application as well as the desired material physical, thermal and other properties. Because most thermal insulation materials exhibit heat flows by a combination of modes (i.e., conduction, radiation, and convection) resulting in property variation with material thickness, or surface emittance, the premise of a pure conduction mode is not valid, therefore, the term ‘apparent’ is implicit in the term thermal conductivity of insulating materials [2–4].

The k-value is dependent on the material density, porosity, moisture content, and mean temperature difference. Published k-values and those reported by manufacturers are normally evaluated at laboratory standard conditions of temperature and humidity to allow a comparative evaluation of thermal performance. However, when placed in their locations in the building envelope, thermal insulation materials are exposed to different temperature and humidity levels depending on the prevailing climatic conditions. Hence, their actual thermal performance may substantially differ from that predicted under standard conditions.

The impact of operating temperature on the thermal performance of insulation materials has been the subject of many studies. The thermal performance of rigid cellular foam insulation was theoretically and experimentally evaluated under different insulation temperatures [5]. The results showed pronounced variations in the k-value with operating conditions. Another set of experiments was conducted on the thermal performance of fiberglass using an attic test module in a guarded hotbox facility [6]. Experiments with one type of loose-fill fiberglass insulation showed that the thermal resistance at large temperature differences was about 35–50% less than that at a small temperature difference. Loose-fill insulation has a somewhat lower thermal resistance at larger temperature differences across the insulation [7]. The impact of temperature difference on the k of some insulation materials produced by Saudi insulation manufacturers has also been evaluated [8]. Thirteen insulation samples were tested at around 35°C mean temperature using a conventional guarded hot plate. The results indicated that k-values exhibit some deviation from the values provided by the manufacturers, which are generally evaluated at a lower mean temperature (i.e., 24°C). In some cases, the thermal conductivity measured at 35°C exceeded the published value by more than 35%.

It is evident, from the above overview, that insulation materials can exhibit pronounced variations in their thermal conductivity values as operating temperatures change. For example, the cooling design dry bulb temperature in Saudi Arabia generally exceeds 40°C [9]. Consequently, the need for a more realistic evaluation of thermal insulation performance in similar harsh climatic conditions is undoubtedly necessary for a more accurate assessment of the thermal performance and for better prediction of energy efficient design.

In addition to the operating temperature, the material moisture content, which is influenced by the ambient humidity level, is another major factor affecting the thermal conductivity of insulation materials [10]. The higher the material moisture content, the higher the thermal conductivity. In buildings, insulation materials used in walls and roofs normally exhibit a higher moisture content when compared to test conditions. The ambient air humidity and indoor conditions, as well as the wall or roof system moisture characteristics, play an important role in determining the moisture status of the insulation material. When conditions are favorable (e.g., hot-humid climates), condensation can occur within the insulation material, raising its moisture content well above the hygroscopic level (i.e., unwetted at RH 98%).

Moisture can diminish the thermal performance of an insulating system. Numerous studies have taken place to assess the impact of moisture content on thermal insulation performance. Benner and Luu studied two parameters of hygroscopic moisture transfer i.e., the equilibrium moisture content and the thermogradient coefficient [11]. The effectiveness of flat roof insulation was found to be reduced by the presence of moisture. Results indicated that a significant increase in energy exchange (gain and loss) through the roof occurred for moisture contents $<1\%$ by volume [12]. Investigations of the performance of polyurethane insulation [13], fiberglass [14] and mineral wool [15] used on heating and cooling pipes subjected to underground water attack were conducted. The effective thermal conductivity and moisture absorption rate were measured. For example, the effective thermal conductivity of the wet fiberglass insulation was found to be many times higher than that of the dry insulation [14]. Another study was conducted to simulate the effect of condensation on the performance of fiberglass slab insulation in a laboratory environmental chamber [16]. Sandberg showed that for cellulose fiber, the effect of moisture on the thermal transmissivity was in the order of 0.001 W/m K within the hygroscopic range [17].

Field, laboratory, as well as theoretical studies [18] on various types of insulation including glass fiber, cellulose fiber, and fibrous biological insulating materials have been carried out. It was concluded that the effectiveness of insulating materials at a higher moisture content is reduced in proportion to the moisture content level. A higher thermal conductivity is obtained due to increased energy transfer by conduction and, under certain conditions, by the evaporation–condensation process, in which moisture moves from warm to cold regions.

Both operating temperature and humidity factors have a significant influence on the thermal performance of insulation materials. However, the objective of this study is to investigate the influence of change in operating temperature on the variation of thermal conductivity and consequently to assess the relative sensitivity of *k*-value of diverse insulation materials commonly used in building envelopes.

Collection and Classification of Insulation Material Samples

Local manufacturers of thermal insulation materials were contacted to collect information about their products and obtain test samples in accordance with the testing requirements. An adequate number of different types of thermal insulation materials was obtained with a standard size of $300 \times 300\,\mathrm{mm}^2$ of different thickness and densities.

Detailed catalog specifications of the collected samples were also obtained for comparison with the test results at a later stage. Obtained samples of insulation materials were screened and then categorized according to their characteristics as well as their intended applications in buildings. A database was developed to classify them according to material description, type, properties, and applications as supplied by their manufacturers. The listing was then utilized to set selection criteria based on material type and application (in light of the stated objectives) for the samples that would be tested. The number of manufacturers producing such materials, the diversity of the physical characteristics including material type, density, and application determined the final number of the selected insulation material specimens. Utilizing the selection criteria, 32 samples were selected for testing. Although the relevant standards require measuring and reporting the nominal *k*-value of the insulation material at 24°C i.e., k_{24} inconsistency in reporting the *k*-value of insulation materials by the manufacturers was noted. For example, thermal conductivity values were reported at either at 10, 20, 23, or 25°C and in many cases the *k*-value was not provided. The selected samples were conditioned and their *k*-values measured at different mean temperatures ranging from 4 to 43°C. Measurement data were analyzed to obtain standard *k*-values and compare their variations with higher mean operating temperatures representing harsh climatic conditions.

THERMAL CONDUCTIVITY MEASUREMENTS

Measurement Apparatus

During the last two decades, many advances have been made in thermal insulation technology, both in measurement techniques and in improved understanding of the principles of heat flow through insulating materials. Consequently, revisions have been made to the measurement of thermal transmission properties. These revisions are considered in the ASTM C518-91 standard [19].

In this study, the Lambda 2300V heat flow meter, a complete PC-automated system, was utilized. It is designed to determine the thermal conductivity of insulating materials in accordance with standard ASTM C518 and ISO 8301 protocols [20]. A $300 \times 300\,\text{mm}^2$ specimen with a thickness ranging from 5 to 100 mm can be placed in the test section between two plates, which are maintained at different temperatures during the test. Upon achieving thermal equilibrium and establishing a uniform temperature gradient throughout the sample, thermal conductivity is determined. The temperature control system is thermoelectric. An external computer system with specialized software controls the measuring apparatus, records and analyzes the data, and prints results.

Measurement Calibration and Procedure

Prior to testing of the selected samples, the measuring instrument was calibrated using a reference sample material (SRM 1450c) with known thermal conductivity values at varying temperatures. To verify the accuracy and ensure reproducibility, the reference sample was tested ten times over an extended period of time. The accuracy and repeatability of the flow meter were confirmed as reported by the manufacturer. k_{24} was determined from the test results using linear regression. The mean error was calculated and found to be around ±0.2% with a standard deviation of ±0.1%.

The selected test specimens of the various insulation materials were kept at normal room conditions for an adequate period of time to satisfy the testing procedure guidelines. The k-value of each of the selected test specimens was then measured at five different mean temperatures ranging from 4 to 43°C (i.e., 4, 10, 24, 38, and 43°C) according to ASTM C1058-92 [21]. The relationship of k variations with mean operating temperature is determined and represented by a linear regression (i.e., to fit a straight line) from which k_{24} is determined. The measure of the data scatter as well as the goodness of the line fit is indicated by the correlation coefficient.

ANALYSIS AND DISCUSSION OF RESULTS

The samples were categorized and grouped, according to their basic material, into seven categories: fiberglass, wood wool, mineral wool, rock wool, polyethylene, polyurethane and polystyrene. Variations of k-values with operating temperature for the above materials category are shown in Figure 1(a)–(d). Generally, it can be stated that higher insulation density results in lower thermal conductivity at a given operating temperature. Possible variations for the same category type can occur due to the different manufacturing processes used in producing such materials. Additionally, it can be seen that the k-values of all insulation materials are affected in variant degrees with operating temperature depending on the material type and density. In all cases, however, higher operating temperatures lead to higher k-values. Variations of k with temperature became more pronounced at lower material densities. This can be attributed to the presence of more air (by volume) in less dense materials, hence creating more active role to the convection and radiative heat transfer mechanisms within the insulation layer resulting in higher thermal conductivity. Figure 1(a) illustrates variations of the thermal conductivity of fiberglass insulation with temperature at different densities. It can be seen that the rate of change of k-value with temperature (as indicated by the line slope) exhibits considerable increase (almost triples) as the density changes from 56.0 to 13.0 kg/m^3. Less pronounced variation is experienced by the rock wool insulation, as can be observed from Figure 1(b). A similar behavior can be noticed for polystyrene insulation shown in Figure 1(c) and (d). Generally, it can be said that variations of the rate of change of thermal conductivity of polystyrene insulation with temperature as density changes is marginal, as it exhibits $<50\%$ change when the density changes from 39.0 to 17.0 kg/m^3.

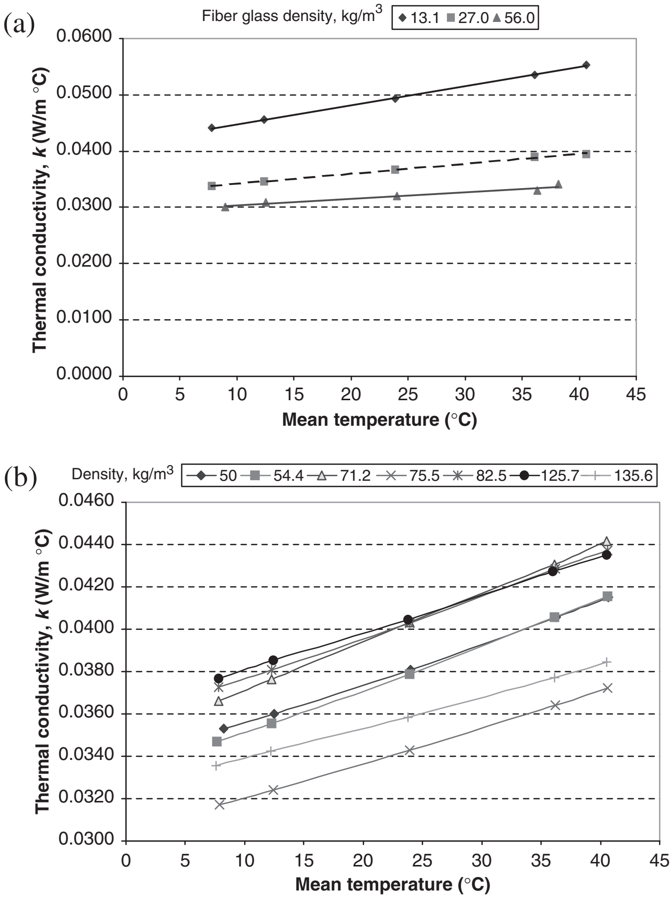

Figure 1. *Thermal conductivity vs operating temperatures. Impact of insulation density on thermal conductivity of various insulation materials: (a) fiberglass insulation material; (b) rock wool; (c) expanded polystyrene; and (d) extruded polystyrene.*

A comparison of the relative variations of operating temperatures on the thermal conductivity values of selected representative samples of insulation materials from each of the categories mentioned is illustrated in Figure 2. It can be seen that the thermal conductivity values of all insulation materials are affected in varying degrees with operating temperature. In all cases, however, a higher temperature leads to higher thermal conductivity values. Furthermore, it can be noted that the thermal conductivity of polyethylene insulation is the most sensitive to temperature increase with a rate of change close to 0.000384 W/m C per °C, while the polystyrene insulation is the least affected with a rate of change of about 0.0001 W/m C per °C.

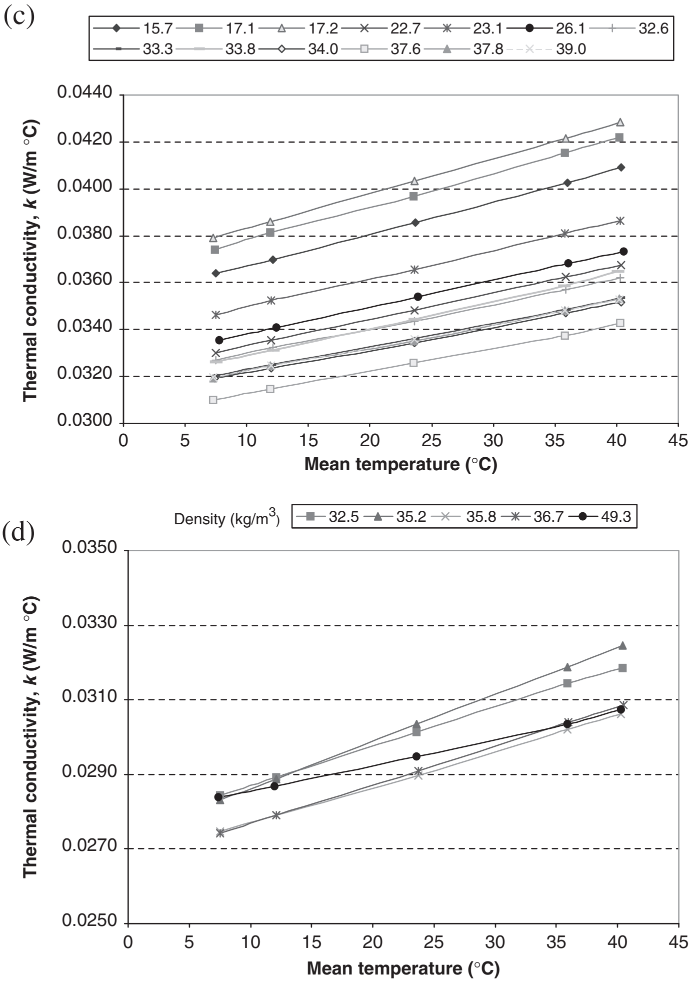

Figure 1. *Continued.*

The relationships of the different types of insulation materials are indicated in Table 1 where more detailed information about material physical and thermal characteristics is given. They are grouped, according to their basic material, into seven categories along with measured values of material density. The relationship of k variations with mean operating temperature is determined and given in a linear regression (i.e., to fit a straight line) from which k_{24} is determined. The slope of the linear relationship of k and mean operating temperatures, and the relative rate of change of k with operating

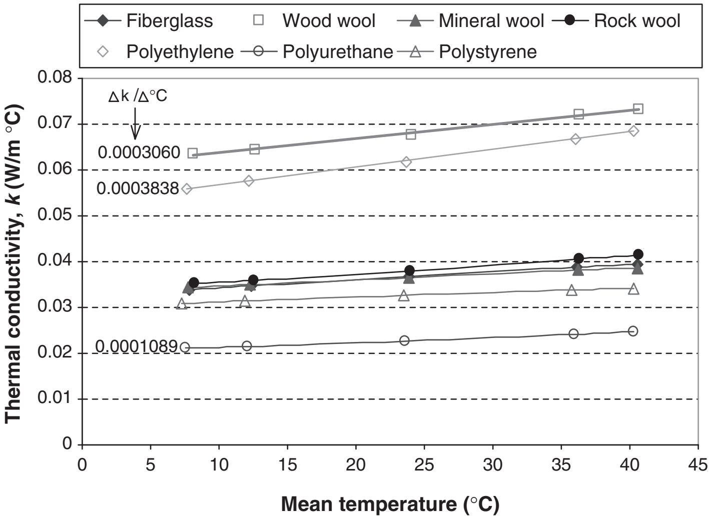

Figure 2. *Comparison of the relative variations of k with mean operating temperatures for different representative samples of insulation materials from each of the seven categories.*

temperatures are also shown. The indicator of the measured data scatter as well as the goodness of the line fit is indicated by the correlation coefficient.

Figure 3(a) compares the k_{24} values for all tested specimens of the different insulation materials. The rate of change of k with operating temperature ($\Delta k/\Delta C$) for all tested insulation samples is illustrated in Figure 3(b). It can be noticed that different insulation materials exhibit considerable variations in the degree of sensitivity of thermal conductivity to operating temperature. For example, the degree of sensitivity of polyethylene insulation thermal conductivity (which exhibits the highest response) to changes in operating temperature is more than five times greater than the response of the extruded polystyrene insulation (which exhibits the lowest). Generally, it can be noticed that thermal conductivity values of fibrous insulation materials (i.e., fiberglass and rock wool) as well as the polyethylene materials are among the highest affected by operating temperature while polystyrene insulation is the least affected. This can be related to the presence of larger quantities of trapped air within the less dense insulation materials, which is expected to enhance heat transfer. It must be noted, however, that the increase of heat transfer is not determined only by the presence of air, but also by the manner that air is trapped within the material. This explains the large variations in responses of materials having almost the same density, as can be seen when comparing fiberglass insulation with the expanded polystyrene with a similar density.

Table 1. The test specimens grouped, according to their basic material, into seven categories along with measured values of material density, the linear relationship of k and mean operating temperatures, k_{24}, and k relative change.

	Material category and type	Manufacturer CODE	Density	'k–T' relationship	k_{24}	$(\Delta k/\Delta C)/k_{24}$	Correlation coefficient, ratio
			kg/m^3	Slope= $\Delta k/\Delta C$	W/m °C	Relative change	
1	**Fiberglass**	**M01**	**13.1**	$k = 0.0003368\,(T) + 0.041433$	0.04952	0.00680	0.999
		M01	27.0	$k = 0.0001775\,(T) + 0.032404$	0.03666	0.00484	0.999
		M01	56.0	$k = 0.0001189\,(T) + 0.029130$	0.03198	0.00372	0.948
2	**Wood wool**	M04	348.2	$k = 0.0003060\,(T) + 0.060724$	0.06807	0.00450	0.994
3	**Mineral wool**	M06	145.4	$k = 0.0001263\,(T) + 0.033425$	0.03645	0.00346	0.999
4	**Rock wool**	**M08**	50.0	$k = 0.0001915\,(T) + 0.033624$	0.03822	0.00501	0.999
		M08	54.4	$k = 0.0002082\,(T) + 0.033024$	0.03802	0.00548	0.999
		M09	**71.2**	$k = 0.0002297\,(T) + 0.034820$	0.04033	0.00570	1.000
		M08	75.5	$k = 0.0001683\,(T) + 0.030341$	0.03438	0.00490	0.999
		M09	82.5	$k = 0.0001970\,(T) + 0.035683$	0.04041	0.00488	1.000
		M09	125.7	$k = 0.0001789\,(T) + 0.036261$	0.04055	0.00441	1.000
		M09	135.6	$k = 0.0001481\,(T) + 0.032393$	0.03595	0.00412	0.999
5	**Polyethylene**	**M02**	**26.0**	$k = 0.0003837\,(T) + 0.052988$	0.06220	0.00617	0.999
6	**Polyurethane**	M13	44.0	$k = 0.0001089\,(T) + 0.020132$	0.02275	0.00479	0.996
7A	**Expanded polystyrene**	**M03**	15.7	$k = 0.0001369\,(T) + 0.035349$	0.03863	0.00354	1.000
		M10	17.1	$k = 0.0001450\,(T) + 0.036337$	0.03982	0.00364	0.999
		M07	17.2	$k = 0.0001490\,(T) + 0.036827$	0.04040	0.00369	1.000
		M03	22.7	$k = 0.0001137\,(T) + 0.032167$	0.03490	0.00326	1.000
		M10	23.1	$k = 0.0001219\,(T) + 0.033728$	0.03665	0.00333	0.999
		M14	26.1	$k = 0.0001152\,(T) + 0.032657$	0.03542	0.00325	1.000
		M10	32.6	$k = 0.0001065\,(T) + 0.031894$	0.03445	0.00309	0.999
		M07	33.3	$k = 0.0000999\,(T) + 0.031291$	0.03369	0.00297	0.999
		M11	33.8	$k = 0.0001177\,(T) + 0.031701$	0.03453	0.00341	1.000
		M07	34.0	$k = 0.0000978\,(T) + 0.031179$	0.03353	0.00292	0.999
		M03	37.6	$k = 0.0000979\,(T) + 0.030287$	0.03264	0.00300	1.000
		M10	37.8	$k = 0.0001016\,(T) + 0.031192$	0.03363	0.00302	0.999
		M10	39.0	$k = 0.0001002\,(T) + 0.031245$	0.03365	0.00298	1.000
7B	**Extruded polystyrene**	M15	32.5	$k = 0.0001045\,(T) + 0.027658$	0.03017	0.00346	1.000
		M05	35.2	$k = 0.0001258\,(T) + 0.027364$	0.03038	0.00414	1.000
		M15	35.8	$k = 0.0000961\,(T) + 0.026741$	0.02905	0.00331	1.000
		M05	36.7	$k = 0.0001040\,(T) + 0.026641$	0.02914	0.00357	1.000
		M15	49.3	$k = 0.0000706\,(T) + 0.027846$	0.02954	0.00239	0.999

Increased thermal conductivity of insulation material due to operating temperature can considerably influence the amount of heat gain or loss in building, hence the magnitude of cooling or heating load. The magnitude of the change in the envelope-induced cooling load resulting from variations in insulation material thermal conductivity due to temperature change, depends on the relative magnitude of the rate of change in thermal conductivity with operating temperature to the nominal thermal conductivity value, k_{24} (evaluated at 24°C).

Combining Figure 3(a) with (b), which compares the rate of change of thermal conductivity with temperature, the expected relative magnitude of change in the envelop-induced load due to thermal conductivity deviation from the nominal value for different insulation materials can be visualized as illustrated in Figure 4. It is apparent that polyethylene

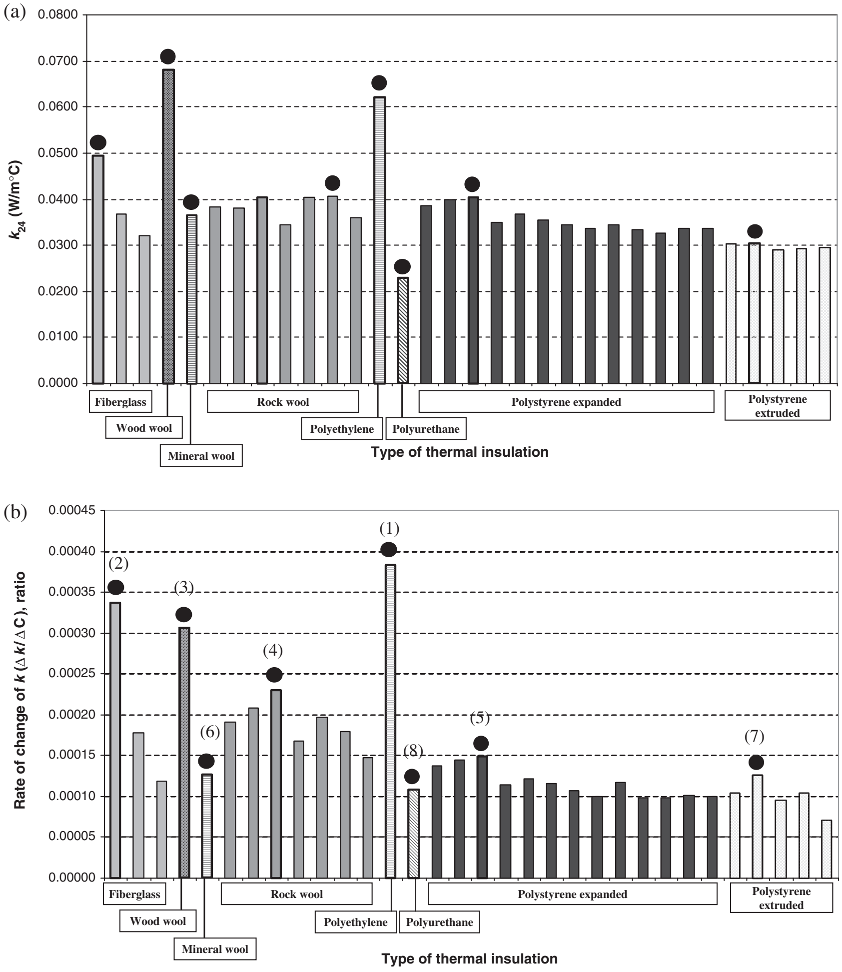

Figure 3. *Comparison of the thermal conductivity for all tested specimens of insulation materials: (a) k_{24} and (b) the rate of change of k with operating temperature ($\Delta k/\Delta C$).*

(density = 26 kg/m^3), fiberglass (density = 13.1 kg/m^3), and rock wool (density from 71.2 kg/m^3) insulation materials trigger the maximum deviation from the nominal value.

CONCLUSIONS

The impact of operating temperature on thermal conductivity has been investigated. Thermal conductivities for various insulation materials were

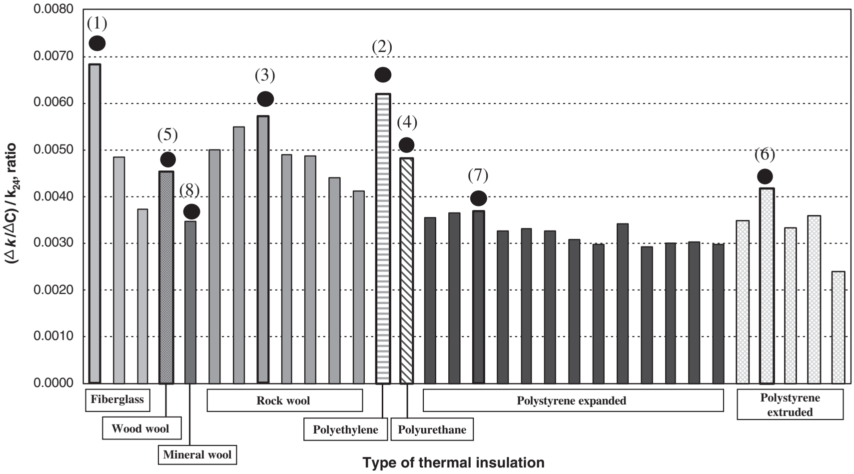

Figure 4. *Comparison of the relative rate of change (sensitivity) of k with temperature* $(\Delta k/\Delta C)/k_{24}$ *for all tested specimens of insulation materials. Materials with the maximum deviation from the nominal value in each of the seven groups of insulation materials are indicated in order.*

measured at different operating mean temperatures using an automated heat flow meter. Results indicate that a higher operating temperature is always associated with higher thermal conductivity in varying degrees depending on the type of insulation material. The polyethylene (density $= 26\,\mathrm{kg/m^3}$) was found to be the most sensitive to changes in operating temperature while the polystyrene (density $= 49.3\,\mathrm{kg/m^3}$) was the least sensitive (see Table 1). Generally, it can be stated that the lower the material density, the higher the effect of operating temperature on material k-value. The relative level of sensitivity to operating temperature for a group of materials, therefore, will vary according to the considered material densities.

Although the relevant standards require measuring and reporting the nominal k-value of the insulation material at 24°C (i.e., k_{24}) inconsistency in measuring and/or reporting the k-value of insulation materials by manufacturers was observed and documented. The results of this study call for the need to set mandatory regulations for thermal insulation material manufacturers to not only abide by the standards requirement but also to provide the k-values of their insulations at higher temperature e.g., 34–35°C or higher to account for their applications in harsh climatic conditions and allow building designers to evaluate the thermal performance of building envelopes considering the actual operating temperature leading to a more realistic assessment of energy requirements. The results can be used as a base for further investigating the influence of humidity and moisture content on the overall thermal performance of insulation materials.

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REFERENCES

1. Budaiwi, I., Abdou, A. and Al-Homoud, M. (2002). Variation of Thermal Conductivity of Insulation Materials Under Different Operating Temperatures: Impact on Envelope-Induced Cooling Load, *Journal of Architectural Engineering*, **8**(4): 125–132.
2. ASTM C168-97 (1997). *Standard Terminology Relating to Thermal Insulating Materials*, ASTM International, www.astm.org
3. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE (2001). *Handbook of Fundamentals*, Chapter 23, Atlanta, GA.
4. Peavy, B.A. (1996). A Heat Transfer Note on Temperature Dependent Thermal Conductivity, *Journal of Thermal Insulation and Building Envelopes*, **20**: 76–90.
5. Aldrich, D.F. and Bond, R.H. (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*, Florida, 2–5 December, pp. 500–509.
6. Wilkes, K.E. and Child, P.W. (1992). Thermal Performance of Fiberglass and Cellulose Attic Insulation, In: *Thermal Performance of the Exterior Envelopes of Buildings V, ASHRAE/DOE/BTECC/CIBSE Conference*, Clear Water Beach, Florida, December 7–10, pp. 357–367.
7. Besan, R.W. and Miller, E. (1982). Thermal Resistance of Loose-Fill Fiberglass Insulation Spaces Heated from Below, In: *Thermal Performance of the Exterior Envelope of Building II, ASHRAE/DOE Conference*, Las Vegas, 6–9 December, pp. 720–733.
8. Al-Hammad, A., Abdelrahman, M.A., Grondzik, W. and Hawari, A. (1994). A Comparison Between Actual and Published *K*-values for Saudi Insulation Materials, *J. Thermal Insulation and Building Envelope*, Technical Note, **17**: 378–385.
9. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE (1997). *Handbook of Fundamentals*, Chapter 26, pp. 47–49, Atlanta, GA.
10. Kochhar, G.S. and Manohar, K. (1995). Effect of Moisture on Thermal Conductivity of Fibers Biological Insulating Materials, In: *Thermal Performance of the Exterior Envelopes of Building VI. ASHRAE/DOE Conference*, Florida, December, pp. 33–40.
11. Benner, S.M. and Luu, D.V. (1982). Thermal Mass-Transfer Coefficient and Equilibrium Moisture Content of Insulating Materials, In: *Thermal Performance of the Exterior Envelopes of Buildings II, ASHRAE/DOE Conference*, Las Vegas, 6–9 December, pp. 1052–1062.
12. Hedlin, C.P. (1988). Heat Flow Through a Roof Insulation having Moisture Contents Between 0 and 1% by Volume, in Summer, *ASHRAE Transactions*, **94**(Part 2): 1579–1594.
13. Chyu, M.C., Zeng, X. and Ye, L. (1997). The Effect of Moisture on the Performance of Polyurethane Insulation used on a District Heating and Cooling Pipe, *ASHRAE Transactions*, **103**(Part 1): 309–317.

14. Chyu, M.C., Zeng, X. and Ye, L. (1997). Performance of Fibers Glass Pipe Insulation Subjected to Underground Water Attack, *ASHRAE Transactions*, **103**(Part 1): 303–308.
15. Chyu, M.C., Zeng, X. and Ye, L. (1998). Effect of Underground Water Attack on the Performance of Mineral Wool Pipe Insulation, *ASHRAE Transactions*, **104**(Part 2): 168–175.
16. Wijesundera, N.E., Hawlader, M.N.A. and Lian, S.C. (1989). Experimental Study of Condensation in Fiberglass Insulation, In: *ASHRAE Far East Conference on Air Conditioning in Hot Climates*, Kaula Lumpur, Malaysia, 25–28 October, pp. 135–139.
17. Sandberg, P.I. (1992). Determination of the Effects of Moisture on the Thermal Transmissivity of Cellulose Fiber Loose-fill Insulation, In: *Thermal Performance of the Exterior Envelopes of Building V, ASHRAE/DOE/BTECC/CIBSE Conference*, Clearwater Beach, Florida, 7–10 December, pp. 517–525.
18. Larson, D.C. and Benner, S.M. (1985). Field and Laboratory Studies of the Thermal Resistance of Moist Building Insulation Systems, In: *Thermal Performance of the Exterior Envelopes of Building III, ASHRAE/DOE/BTECC Conference*, Florida, 2–5 December, pp. 527–538.
19. ASTM C518-91 (1991). *Standard Test Method for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter Apparatus*, ASTM International, www.astm.org
20. Lambda 2000 Series (1997). *Heat Flow Meter Thermal Conductivity Instrumentation*, Operation Manual, Holometrix Inc., USA.
21. ASTM C1058-92 (1991). *Standard Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation*, ASTM International, www.astm.org