CHALLENGES RELATED TO MEASURING AND REPORTING TEMPERATURE-DEPENDENT APPARENT THERMAL CONDUCTIVITY OF INSULATION MATERIALS

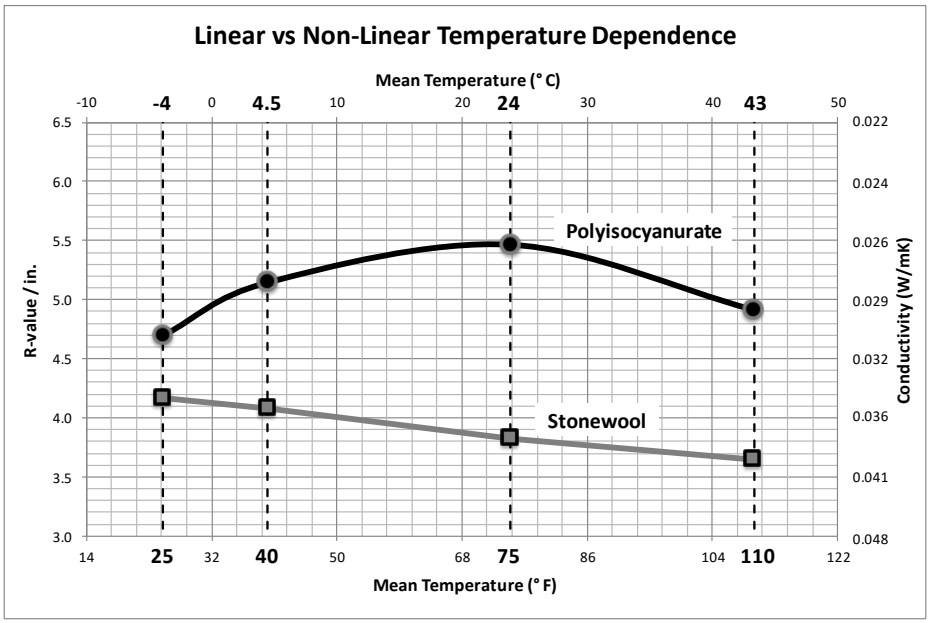
C. J. Schumacher, RDH Building Science Laboratories
J. F. Straube, University of Waterloo

EXTENDED ABSTRACT

In North America, the apparent thermal conductivity (and R-value) of building insulation materials is commonly reported at a mean temperature of 24°C (75°F) and practitioners typically assume thermal properties remain constant over the range of temperatures that are experienced in building applications. Researchers have long known and acknowledged the fact that the thermal properties of most building insulation materials change with temperature. There has been little more than academic reason to measure and report this effect. However, interest in temperature-dependent thermal performance has grown with the introduction of new materials, increasing concerns regarding energy performance, and the development of tools transient energy, thermal, and hygrothermal simulation software packages (e.g. Energy Plus, HEAT2, WUFI etc.) that have capacity to account for temperature-dependence.

ASTM C1058, "Standard Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation" has for decades recognized temperature-dependence and recommends six mean temperatures for the testing of insulation used in "Building Envelopes". A growing number of sources (i.e. manufacturers, research groups, etc.) are reporting apparent thermal conductivity at four or more of these mean temperatures. The most commonly referenced are: -4, 4.5, 24 and 43°C (25, 40, 75 and 110°F).

In many cases, the temperature dependency is approximately linear over the temperature interval of interest in building insulation applications and no further testing or analysis is necessary. However, some insulation products, particularly refrigerant-blown closed-cell foam insulation materials, can exhibit strongly non-linear behavior.



This presentation considers two methods to measure, analyze, and report the temperature-dependent apparent thermal conductivity or resistance of building insulation products:

1. The Thermal Conductivity Integral (TCI) Method: This method is described in ASTM C1045, "Standard Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions." Apparent thermal conductivity is measured in accordance with ASTM C518, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus." Measurements are made at five of the mean temperatures recommended in ASTM C1058: -4, 4.5, 10, 24 and 43°C (25, 40, 50, 75 and 110°F), and with the ASTM C1058-recommended temperature difference of 27.8°C (50°F). A least-squares fit is performed to the experimental data of the integral of the functional form obtained in accordance with the method described in ASTM C1045. In theory, this fit can be used to predict the apparent-thermal conductivity for any mean temperature within the range of those tested.

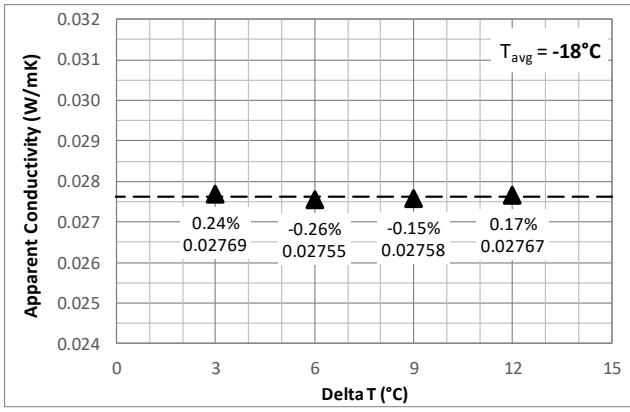
2. The "Decreasing Delta-T Method": This method, proposed by Schumacher (2013), seeks to quantify the apparent thermal conductivity (for any given mean temperatures) as the temperature difference approaches zero, effectively eliminating temperature-dependence from the measurements. Apparent thermal conductivity is measured in accordance with ASTM C518, at as many mean temperatures as practical. For each mean temperature, measurements are made at a series of decreasing temperatures differences, for example, 28.7, 12, 9, 6 and 3°C (21.6, 16.2, 10.8 and 5.4°F), a least-squares fit is performed, and the trend is extrapolated to a delta-T of zero. ASTM C1045 (Note 9) and C1058 (clause 4.4) recognize the benefit of measuring at more mean temperatures and smaller temperature differences. The extrapolation to delta-T of zero is a natural extension of this approach.

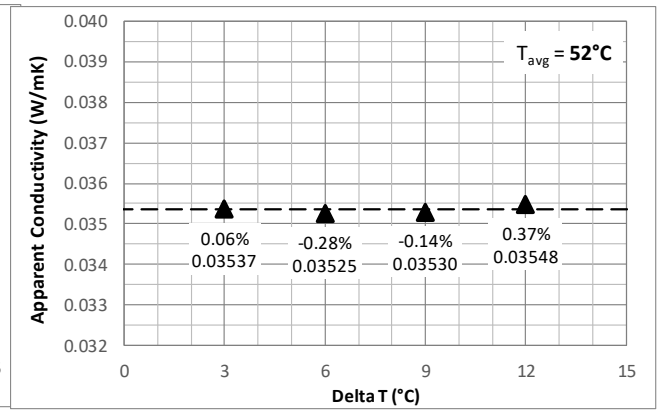
In theory the TCI and Decreasing Detla-T methods should produce close to the same curve when applied to materials that exhibit approximately linear temperature-dependence.

A small round-robin measurement program was established to explore the applicability and limitations of the two measurement and analysis methods: two different samples of 50 mm (2 in.) thick polyisocyanurate (polyiso) roof insulation were measured at three research laboratories. The results show good reproducibility across labs.

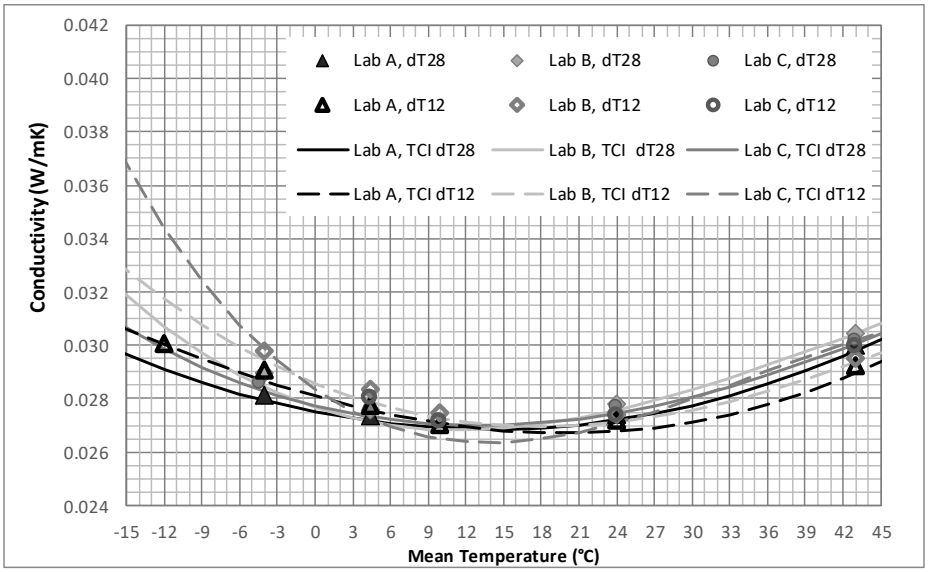
Full Data Set			Sample 1			Sample 2		
Segment	Mean Temp	Delta T	Lab A	Lab B	Lab C	Lab A	Lab B	Lab C
B1	-12	12	0.03415			0.03006		
B2	-12	9	0.03530			0.03050		
B3	-12	6	0.03699			0.03112		
B4	-12	3	0.03951			0.03226		
A1c	-4.3	28.7						0.02860
A1	-4	28	0.02958			0.02814		
A1b	-4	22		0.03080			0.02894	
A2	-4	12	0.03210	0.03282		0.02908	0.02980	
A3	-4	6	0.03445			0.02987		
B5	-4	3	0.03731			0.03119		
A4	4.5	28	0.02773	0.02786		0.02737	0.02757	0.02760
B6b	4.5	16					0.02827	
A5	4.5	12	0.02900	0.02961		0.02775	0.02834	0.02801
B6c	4.5	8		0.03133			0.02907	
B6	4.5	6	0.03105			0.02847		0.02866
B7b	4.5	4		0.03379			0.03030	
B7	4.5	3	0.03247			0.02900		0.02926
B8	10	12	0.02702	0.02747		0.02702	0.02747	0.02714
B9	10	6	0.02748	0.02824		0.02713	0.02902	0.02721
A6	24	28	0.02577	0.02593		0.02743	0.02778	0.02768
A7	24	12	0.02547	0.02547		0.02719	0.02742	0.02737
A8	43	28	0.02800	0.02814		0.03000	0.03045	0.03019
A9	43	12	0.02778	0.02770		0.02926	0.02951	0.02996

Further, the labs demonstrated the capacity to use their commercial Heat Flux Measurement Apparatus (HFMA) to measure apparent thermal conductivity of EPS and semi-rigid fiberglass insulation (ductboard) calibration samples, at small temperature differences. The researchers were thus confident in the data produced for the two polyisocyanurate roof insulation samples.

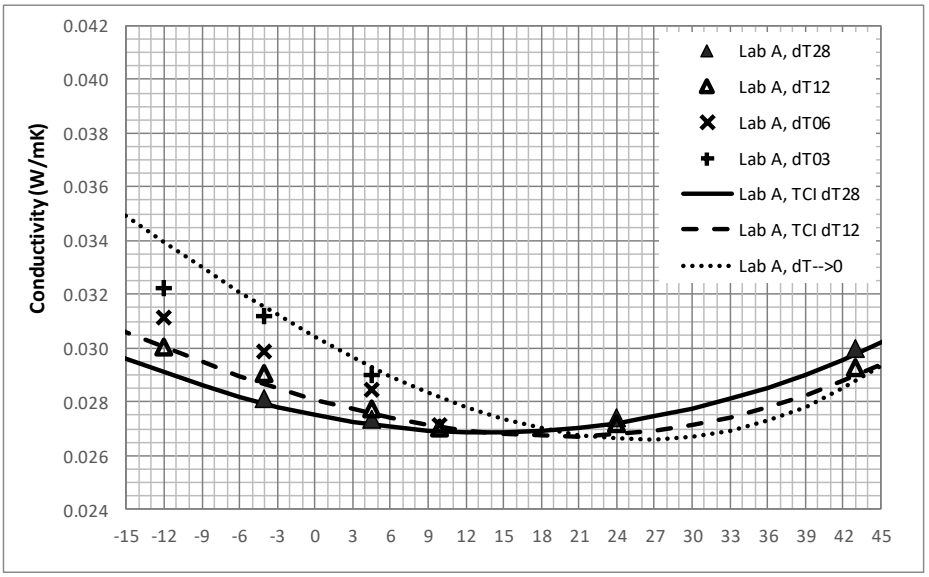




The polyiso insulation data were first analyzed using the TCI method, assuming an equation with cubic form. The presentation elaborates on this process. Analysis of data from the deltaT=28°C tests results in a different temperature-dependence curve than that produced by analysis of the deltaT=12°C tests. Neither of the TCI curves adequately predicts the results for the small deltaT tests.



The polyiso insulation data were further analyzed using the proposed Decreasing Delta-T method. Again, the presentation provides a detailed explanation of the procedure. The Decreasing Delta-T method resulted in a different temperature dependency curve than either of the curves produced using the TCI method.



The Decreasing Delta-T method might be expected to have an advantage over the TCI method because the analysist does not need to choose an equation form as the basis of the analysis. It is plausible that the cubic equation form assumed for the TCI portion of this work does not adequately capture the heat transfer mechanisms in the polyisocyanurate samples tested. The researchers hoped the Decreasing Delta-T method would solve this problem, yet none of the curves produced using the TCI or the Decreasing Delta-T methods successfully predict the measured apparent thermal conductivity over the range of temperature differences considered (e.g., in the preceding image, 28, 12, 6, 3°C). This study raises questions about appropriate methods to measure and report apparent thermal conductivity for materials that exhibit have a highly non-linear temperature-dependence. The presentation concludes with recommendations for further research as well as ongoing measurement and reporting practices.