THERMAL RESISTANCE OF ROOF PANELS AND IN-SITU CALIBRATION OF HEAT-FLUX TRANSDUCERS

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ABSTRACT

The dynamic insulation efficiency tester, DIET, has been used to measure the apparent thermal conductivities, k_a, of four board-insulations used in roofing applications. The k_a values were calculated from steady-state temperature and heat flux measurements. The experimental results were also used to obtain calibration factors for heat flux transducers imbedded in the panels.

Apparent thermal conductivities of polyisocyanurate, polystyrene, fiberglass, and fiberboard panels have been determined in the range of 298 to 330 K and described to within ±1% by linear functions of temperature.

The heat flux measurements obtained with DIET were used to obtain calibration factors for heat flux transducers imbedded in panels to be used in roof-tests assemblies. The factors relating transducer electrical output to heat flux ranged from 55% to 70% of the manufacturer-supplied factors that were obtained at heat flow rates much higher than the present case. These results demonstrate the need for in-situ calibration of heat flux transducers at heat flow rates near those to be used for thermal performance evaluations.

INTRODUCTION

The measurement of apparent thermal conductivity, k_a, with constant temperature boundaries and an apparatus containing a thin electrical resistance heater as a heat source, has been discussed by Niven and Geddes (1912), Gilbo (1951), and Hager (1960, 1962, 1969). The idea of using a thin electrical heater in an unguarded thermal test apparatus has been discussed by Jury et al. (1978) for radial heat flow measurements and by Moore et al. (1974, 1983) for longitudinal heat flow. The concept of a large unguarded system with a relatively thin heater was the basis for a flat insulation tester, discussed in detail by McElroy et al. (1985) and Graves et al. (1985). The tester, named the dynamic insulation efficiency tester (DIET), can be used to measure k_a under steady-state conditions or to obtain transient heater temperatures from an initial isothermal condition until steady-state conditions are realized (McElroy et al. 1985).

DIET provides an absolute method for the determination of k_a that is an alternative to the guarded hot plate (ASTM 1983) or the heat flow meter (ASTM 1983). DIET is used to obtain steady-state measurements of heat flux (q/A) and temperature difference (ΔT) across a horizontally mounted rectangular specimen of known thickness (ℓ) from which k_a is calculated with Fourier's law for one-dimensional heat flow:

$$\frac{q}{A} = -k \frac{dT}{dx} \approx k_a \frac{(T_2 - T_1)}{\ell} . \quad (1)$$

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One-dimensional vertical heat flow across the central region of a test specimen occurs in DIET because of the size of the apparatus rather than edge guarding as is the case for the guarded hot plate (ASTM 1983). A thermal modeling program (Turner et al. 1977) was used to verify that steady-state one-dimensional heat flow exists in a central region of the screen for insulation samples up to about 0.15 m thick and R-values of 18.7 $ft^2 \cdot h \cdot F/Btu$ (3.3 $m^2 \cdot K/W$) Thermal modeling results have been reported in previous publications (Moore et al. 1983; McElroy et al. 1985; and Graves et al. 1985).

The measurements of k_a for an insulation at given thickness in DIET typically include k_a values at three to ten screen heater temperatures ranging from 300 to 360 K with the temperature of the plates near 297 K. DIET can be used to determine k_a of a compressible insulation as a function of temperature and density.

DIET can be used to measure heat flow up, heat flow down, or heat flow across a pair of rectangular specimens above and below the screen heater. Heat flow in one direction is accomplished by matching the temperature of one boundary to the steady-state screen temperature so that heat flow across an insulation specimen between the screen and the plate is small compared to the rate of heat transfer in the test specimen. Equation 2 is used to calculate k_a for measurements made with heat flow in two directions while Equation 3 is used for heat flow across a single sample:

$$k_a = I \cdot V \cdot \ell / 2 \cdot A \cdot \Delta T \qquad (2)$$

$$k_a = [I \cdot V - (k_B \cdot A \cdot \Delta T_B)/\ell_B] \cdot \ell / A \cdot \Delta T \ . \qquad (3)$$

The apparatus can be used to obtain dynamic thermal data in the form of screen temperatures recorded electronically as a function of time. DIET has been used with an electronic data logger to record screen temperatures as a function of time after applying constant DC power input to the screen heater. Dynamic testing has been carried out with the plate-specimens-heater system initially isothermal. The time-temperature records have been analyzed numerically to obtain thermal diffusivity information (Wood 1985) and to explore use of the two-flux model for radiative transport (Tong 1985).

A detailed determinate error analysis for DIET has been reported (Graves et al. 1985). The analysis shows a total determinate uncertainty in k_a of 1.70% with ΔT of 5 K and 0.73% with ΔT of 30 K. The corresponding most probable errors were found to be 1.20% and 0.37%. Further validation of DIET results for k_a are provided by comparisons with materials supplied and tested by the National Bureau of Standards. The k_a obtained by the National Bureau of Standards and DIET on specimens of Standard Reference Material 1450b and National Bureau of Standards fiberglass transfer standard differed by less than 0.6% and 0.08% respectively.

DIET has been used to measure k_a of commercial fiberglass batt thermal insulation, spray-applied cellulosic insulations, spray-applied mineral fiber products, powder-filled evacuated panels, and a number of board insulations. This paper reports thermal conductivities obtained for four board insulations used in roofing applications.

EQUIPMENT DESCRIPTION

DIET uses an electrically powered 0.91 m by 1.52 m fine wire screen that is 6.4 x 10^{-4} m thick as a heat source. The screen heater is typically sandwiched between matched rectangular slabs that are in turn bounded by 1.14 m x 1.75 m temperature-controlled plates fabricated from 0.012 m thick copper stock as shown in Figure 1. The steady-state temperature difference across test specimens is measured with 36-gauge Type E thermocouples attached to the screen heater and to the copper plates. Fifteen thermocouples are attached to the wide surface of each copper plate with thermally conducting epoxy. Ten thermocouples are thermally bonded to the screen. An average screen temperature for use in Equation 2 or 3 is typically obtained from the four centrally positioned thermocouples shown in Figure 2. The thermocouples were referenced to an ice-water bath and read with a precision potentiometer.

The electrical power to the central region of the screen was obtained from voltage measurements on the edge of the screen spaced 0.305 m on each side of the centerline. The

DC current supplied by a stable power supply was determined from the voltage drop across a 0.01 ohm standard resistor that was electrically in series with the screen heater.

Insulation thickness is determined from the length of hollow cylindrical tubes used to separate the screen heater and the copper plates. Tubes of various lengths are available for testing a given insulation at different thicknesses and densities in the case of the compressible materials.

Heat fluxes across a material installed in DIET are calculated from the power input to the screen heater. Heat flux is $I \cdot V/2 \cdot A$ for two-sided measurements and $[I \cdot V - (k_B \cdot A \cdot \Delta T_B)/\ell_B]/A$ for single-sided measurements. Direct measurement of the heat flux permits calibration of heat flux transducers placed in the region between the screen heater and the copper plates. Results obtained with DIET for heat flux transducer calibrations are the second topic to be discussed.

ROOF PANEL DATA

Apparent thermal conductivities have been measured as a function of temperature for roof panel insulations made from fiberboard, fiberglass board, polyisocyanurate, and polystyrene. Roof panel specimens were installed on both sides of the screen heater in DIET and mean specimen temperatures ranged from 298 to 330 K. Table 1 contains densities and thicknesses for the four roof panel specimens that were tested. Panel material was stacked to provide thicknesses needed for testing.

Results for k_a for each of the four roof panel materials tested are given in Table 2. The variation of k_a with temperature was found to be linear in the interval tested. The method of least squares was used to obtain the constants in Equation 4, which gives k_a as a function of temperature. The values for a and b listed in Table 2 describe the measured k_a

$$k_a = a + bT \qquad (4)$$

to be better than 0.5% in all cases.

HEAT FLUX TRANSDUCER CALIBRATIONS

An important feature of the thermal testing of roof insulations was the in-situ calibration of heat flux transducers imbedded midway in the upper test stack. The in-situ calibration was done in conjunction with use of the panels in the Roof Test Facility. The heat flux transducers were 0.0508 m on each side and 0.00414 m in thickness. The transducers were positioned at the center of the test stack halfway between the electrically powered screen and the upper copper plate of DIET. The heat flux calculated from screen voltage drop and current was taken to be the heat flux across the transducer. Corrections for variation in heat flux with position due to differences in k_a of the transducer and k_a of the surrounding insulation have not been made, but preliminary results indicate that the calibration factor correction may be significant.

Table 3 shows results obtained for the steady-state voltage from each transducer and the measured heat flux. In each case a calibration factor $(Btu/ft^2 \cdot h)/MV$ has been calculated for comparison with the factor supplied by the manufacturer. The calibration factors obtained in this work were at a heat flux much lower than the mid-range of the transducer. The results indicate the importance of in-situ calibration for flux levels near those to be measured.

CONCLUSION

The thermal test apparatus DIET has been used to measure k_a for insulation materials marketed for use as roof insulation. The test results were obtained for thickness representative of field application and correlated with temperature. The screen tester concept proved to be convenient for such measurements.

In-situ calibration of heat flux transducers mounted at the center of the panel stacks that were tested yielded calibration constants that were 55 to 70% of the manufacturer-supplied constants. The in-situ calibrations were done for heat fluxes well below the stated mid-range for the transducers, indicating the necessity for calibration of the transducers for the intended use environment and flux level.

NOMENCLATURE

a, b	=	constants in Equation 4.
A	=	area, m^2
I	=	DC current, amperes
k	=	thermal conductivity, W/m•K
k_a	=	apparent thermal conductivity, W/m•K
ℓ	=	specimen thickness, m
q	=	heat flow rate, W
T	=	temperature, K or °C
V	=	DC voltage, volts
X	=	position coordinate

Subscript B value for guard material in one-sided heat flow test.

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NBS. "Fiberglass Batt Transfer Standard." A commercial grade product having a density of 10.4 kg/m^3 (air included).

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TABLE 1

Density and Thickness of Roof Panel Test Specimens

Material	Average Panel Thickness in. (m)	Pieces in Stack	Specimen Thickness in. (m)	Density $lb/ft^3 (kg/m^3)$
Fiberboard	0.94 (0.0239)	6	5.937 (0.1508)	19.22 (307.9)
Fiberglass	0.98 (0.0249)	4	3.926 (0.0997)	12.85 (205.8)
Polysio-cyanurate	1.45 (0.0368)	2	2.974 (0.0755)	2.291 (36.7)
Polystyrene	1.00 (0.0254)	2	4.642 (0.1179)	1.028 (16.5)
	1.25 (0.0318)	2		

TABLE 2

Values for a and b in the Equation $k_a = a + bT$*

Material	a	b	Temperature (°C)
Fiberboard	0.05305	0.13151×10^{-3}	36-57
Fiberglass	0.03604	0.98246×10^{-4}	31-40
Polyisocyanurate	0.02175	0.12040×10^{-3}	26-46
Polystyrene	0.03443	0.14799×10^{-3}	26-50

*k_a in W/m•K, T in °C

TABLE 3

Calibration Results for Four Heat Flux Transducers

Material	Flux $Btu/ft^2 \cdot hr$	Transducer Voltage (mv)	at $\bar{T}$ (°C)	Calibration Constant $(Btu/ft^2 \cdot hr)/mv$	Manf. Supplied Constant
Fiberboard	2.8674	4.0589	36.26	0.7064	1.037
	8.1259	11.6579	56.41	0.6970	
Fiberglass	1.7046	2.4263	31.33	0.7026	
	2.7027	3.8978	35.29	0.6934	1.075
	3.8658	5.6020	39.70	0.6901	
Polyisocyanurate	0.9149	1.3816	26.44	0.6622	
	2.1543	3.2679	34.73	0.6592	1.181
	4.7238	7.2938	45.66	0.6476	
Polystyrene	0.8967	1.1904	26.81	0.7533	
	2.2170	2.9704	34.80	0.7464	1.072
	4.1482	5.6164	43.25	0.7386	
	5.7384	7.7870	49.88	0.7369	

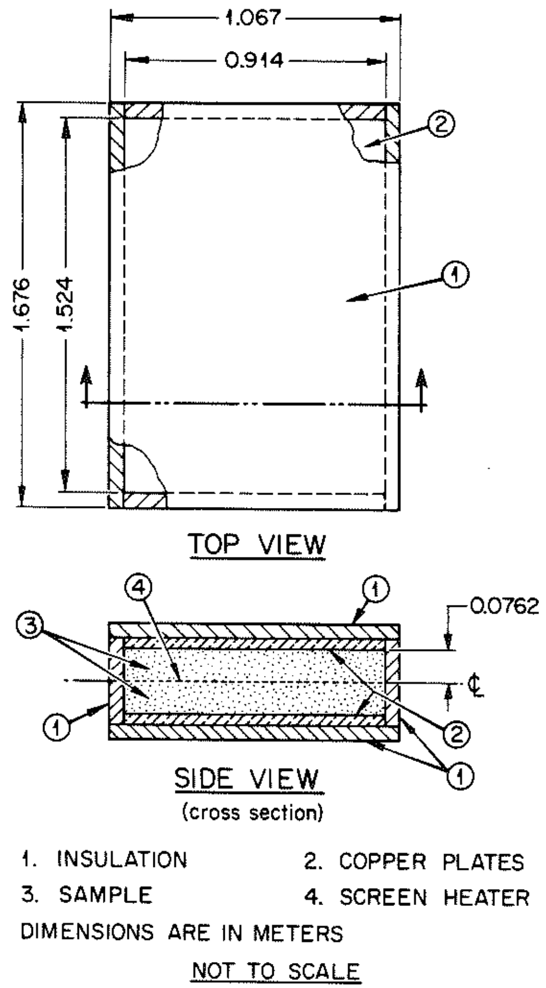

Figure 1. Top and side views of the thermal test apparatus (DIET)

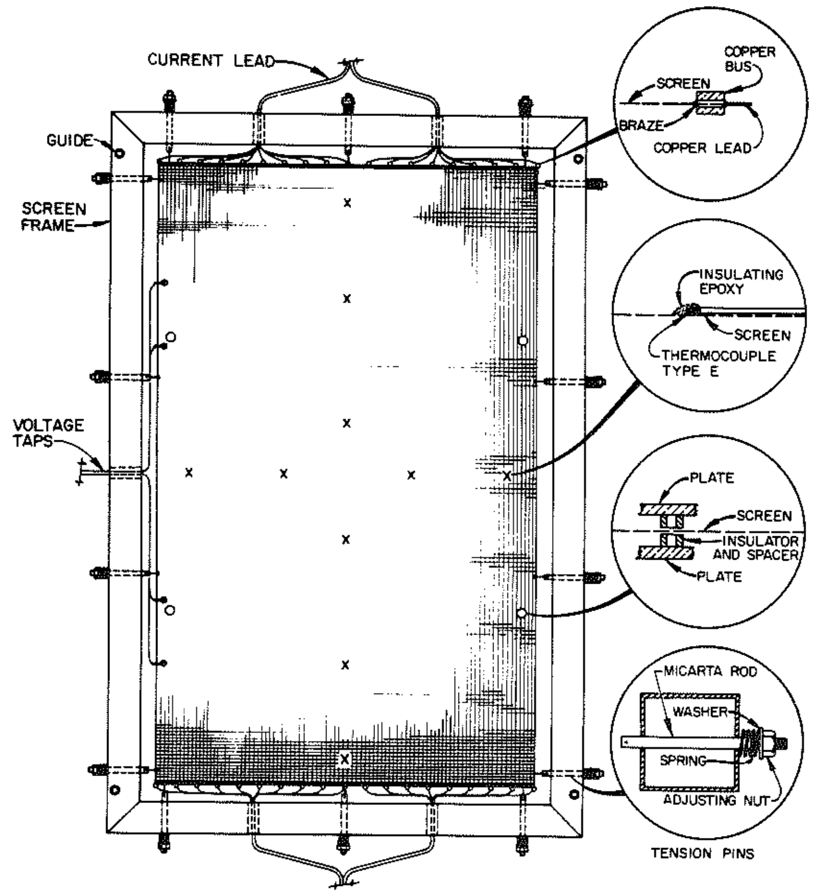

Figure 2. Details of the screen heater used in DIET