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Calibration of a Heat Flow Meter Apparatus

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ABSTRACT: A series of calibration measurements was done on a 600 mm × 600 mm heat flow meter apparatus. Several specimens of medium density glass fiber insulation and expanded polystyrene insulation were used as transfer standards. The thickness of these transfer standards varied from 25 to 160 mm. The mean temperature varied from 0 to 40°C and the temperature difference across the insulation specimens varied from 10 to 40 K. Measurements included cases in which the ambient temperature of the test assembly was either maintained within 1 K of the mean temperature, or those with only edge insulation, and an enclosure for the whole test assembly in order to reduce the edge heat losses. A total of 91 sets of measurements were made. Each set of measurements included two sub-sets, one for the warmer(hot) plate and the other for the colder(cold) plate and each sub-set included a heat flow transducer output and the temperatures on either side of the transducer assembly. For 90 out of the 91 sets of measurements, the steady state heat flux across the specimen was correlated, with a standard deviation of 2%, to a simple linear relation between the average transducer output and the average of the surface temperatures of the two transducer assemblies.

INTRODUCTION

THE HEAT FLOW meter apparatus is widely used to measure the thermal resistance of insulating materials. Tye and McElroy [1] have commented on this as follows. "It is, in every respect, a very good technique for evaluat-

ing the thermal performance of thermal insulation materials provided it is used correctly. A very important factor with respect to the use of the method is heat flow meter calibration, especially of the whole apparatus." De Ponte and Maccato [2] have theoretically analyzed some of the aspects of heat flow meter calibrations. International standards such as the ASTM Standards C 518[3] and C 1132 [4] and the ISO Standard 8301 [5] attempt to standardize the construction, calibration and application of the heat flow meter apparatus. In spite of these attempts, within the measurement community a number of questions are repeatedly asked:

- Does the calibration depend on the nature of the test specimen?
- Does the thickness of the specimen play a role?
- How does the temperature difference across the specimen affect the calibration?
- What is the effect of the mean specimen temperature on the calibration?

There are evidences in the literature that all these questions are relevant. But how significant are the effects, within the limitations of the methodology?

Based on many years of experience on heat flow meter apparatus methodology, a series of measurements were done at the Institute for Research in Construction during a period of six months. The measurements were planned to answer the following question: Can the physical quantities measured on a heat flow meter apparatus, such as the transducer outputs and surface temperatures, under steady state heat flux conditions across any given transfer standard specimen (used for calibrating a heat flow meter apparatus) be correlated, within 2%, to the heat flux?

The measurements were also planned to include some of the effects mentioned generally in the four questions asked by the measurement community. Thus, six specimens of medium density glass fiber insulation ($\approx 50 \text{ kg} \cdot \text{m}^{-3}$) or expanded polystyrene insulation were used as the transfer standards. The glass fiber specimens were used at thicknesses of 26, 52 and 150 mm. There were two separate specimens each with a thickness of 150 mm. The polystyrene specimens were used at thicknesses of 73 and 158 mm. The mean temperature of the test specimen in the apparatus was varied between 0 and 40°C. The temperature difference across the specimens was varied from 10 to 40 K. In many measurements, the test assembly, that includes 25 mm of glass fiber insulation around the perimeters (to reduce the edge heat losses), was kept at an ambient temperature that matched the mean specimen temperature within 1 K. In others no special attempt was made to control the ambient temperature, but the edge losses were reduced using glass fiber insulation around the perimeters and a box enclosure, made out of polyisocyanurate board insulation, for the whole test assembly.

This technical note briefly describes the heat flow meter apparatus used for the measurement and presents the results from 91 independent measurements done on the six transfer standard specimens and the calibration procedure adopted.

THE HEAT FLOW METER APPARATUS

The apparatus used for the measurements reported is a 600 mm $\times$ 600 mm one. It conforms to ASTM Standard C 518 [3]. As shown in configuration B of Figure A2.1 of the standard, each plate of the apparatus has a built-in heat flow transducer. The plates are maintained at constant temperatures by circulating thermostated fluids in a counter-flow pattern as shown in case (b) of Figure A2.2 of the standard. The details of the plate assembly are shown in Figure 1. All measurements are done in a horizontal configuration with the heat flux vertically upwards. As shown in Figure 1, enclosed in circles, three quantities are measured out of each plate, under steady state conditions. These are:

1. Output, E (mV), from the heat flow transducer
2. Temperature, T_p ($^{\circ}\text{C}$), of the inner surface of the aluminium plate and
3. Temperature, T ($^{\circ}\text{C}$), of the inner surface of the plate assembly

The central 250 mm $\times$ 250 mm area of the transducer is a thermopile with 1800 copper-constantan junctions. The temperatures T_p and T are the averages of four separate measurements done in corresponding central areas. Calibrated thermocouples are used as sensors for these measurements. Addi-

FIGURE 1. Schematics of the plate assembly; the three quantities that are measured out of each plate assembly are enclosed in circles (see text).

tional thermocouples mounted uniformly across the full areas are used to ensure isothermal planes in the assembly. Usually the temperature distribution in either area is uniform within 0.05 K.

RESULTS

The results from 91 individual measurements on the six transfer standards are listed in Table 1. These measurements were carried out over a period of six months.

ANALYSIS OF THE DATA

The steady state heat flux, Q_{ref} (W/m^2), is calculated from the information available on each transfer standard from guarded hot plate measurements conforming to ASTM Standard C 177 [6]. These calculated values for each measurement are listed in Table 2. The objective of the analysis is to find the best correlation between the steady state heat flux and the six quantities measured to represent each set given in Table 1.

As the starting point, the relation between Q_{ref} and E for each plate was examined. As shown in Figure 2 this relation is linear. Hence for each plate one may calculate a "sensitivity factor" S [$W/(m^2 \cdot mV)$] [4] as:

$$S = \frac{Q_{ref}}{E} \quad (1)$$

The results from such a calculation are shown in Figure 3, where S is plotted against Q_{ref} . It can be seen that for either plate all the 91 values of S fall within 4% of a respective mean value. If one does the calculation as

$$S = \frac{Q_{ref}}{E_{avg}} \quad (2)$$

where E_{avg} is calculated as:

$$E_{avg} = \frac{E_h + E_c}{2} \quad (3)$$

The results will be as shown in Figure 4. Now it can be seen that all the 91 results falls within 2% of $10.7 W/(m^2 \cdot mV)$. However, the distribution of the 91 values show that the majority of them fall within 10.5 and 10.7 $W/(m^2 \cdot mV)$. With so many results in hand, one would expect an even dis-

Table 1. Experimental data on the six transfer standards. The subscripts h and c denote hot and cold respectively. The rest of each symbol has the same meaning as given in the section on the apparatus.

No	T_{hp} °C	T_h °C	T_{cp} °C	T_c °C	E_h mV	E_c mV
1	35.41	35.13	12.14	12.41	0.4645	0.4710
2	11.49	11.24	-11.40	-11.10	0.4071	0.4255
3	15.98	15.73	-6.54	-6.30	0.4107	0.4233
4	21.32	21.07	-1.18	-0.94	0.4166	0.4320
5	26.20	25.94	3.67	3.91	0.4310	0.4385
6	31.15	30.87	8.62	8.86	0.4463	0.4418
7	36.13	35.85	13.45	13.70	0.4580	0.4563
8	41.25	40.97	18.37	18.63	0.4740	0.4706
9	46.33	46.06	23.47	23.74	0.4851	0.4793
10	51.20	50.92	28.40	28.67	0.4987	0.4869
11	29.12	29.00	18.85	18.97	0.2032	0.2076
12	39.33	38.98	8.53	8.88	0.6118	0.6199
13	15.42	15.31	4.95	5.07	0.1889	0.2060
14	25.22	24.89	-6.00	-5.66	0.5768	0.5924
15	35.48	34.94	12.73	13.29	0.9643	0.9886
16	11.39	10.88	-11.70	-11.20	0.9039	0.9090
17	16.59	16.07	-6.74	-6.20	0.9288	0.9373
18	21.49	20.96	-1.59	-1.04	0.9336	0.9463
19	26.46	25.93	3.39	3.94	0.9457	0.9657
20	31.36	30.82	8.26	8.83	0.9656	0.9861
21	41.65	41.09	18.44	19.02	1.0072	1.0323
22	46.51	45.94	23.34	23.93	1.0246	1.0504
23	51.57	50.99	28.43	29.03	1.0468	1.0714
24	35.58	35.03	12.45	13.02	0.9844	1.0038
25	29.23	28.98	18.76	19.01	0.4448	0.4568
26	39.76	39.01	8.27	9.05	1.3387	1.3634
27	15.33	15.09	4.88	5.13	0.4235	0.4315
28	25.65	24.95	-5.71	-4.96	1.2797	1.2819

(continued)

Table 1. (continued).

No	T_{hp} °C	T_h °C	T_{cp} °C	T_c °C	E_h mV	E_c mV
29	35.66	34.97	12.29	13.02	1.2578	1.2753
30	11.60	10.96	-11.60	-10.90	1.1494	1.1418
31	16.66	16.01	-6.67	-5.99	1.1787	1.1735
32	21.73	21.06	-1.83	-1.13	1.2130	1.2111
33	26.60	25.93	3.27	3.97	1.2208	1.2266
34	31.53	30.85	8.17	8.88	1.2424	1.2542
35	41.83	41.12	18.33	19.08	1.2945	1.3185
36	46.65	45.92	23.25	24.01	1.3173	1.3423
37	51.73	50.98	28.12	28.90	1.3588	1.3861
38	35.15	34.46	11.96	12.68	1.2568	1.2679
39	29.29	28.97	18.79	19.12	0.5719	0.5779
40	39.84	38.90	8.40	9.38	1.7131	1.7190
41	15.34	15.04	4.76	5.08	0.5470	0.5500
42	26.03	25.12	-5.93	-4.97	1.6714	1.6425
43	29.28	28.96	18.79	19.11	0.5763	0.5766
44	32.00	31.52	16.07	16.56	0.8753	0.8746
45	34.60	33.96	13.35	14.01	1.1659	1.1653
46	37.24	36.45	10.60	11.43	1.4615	1.4584
47	39.97	39.02	7.94	8.94	1.7538	1.7493
48	42.58	41.47	5.35	6.51	2.0369	2.0304
49	45.32	44.04	2.78	4.11	2.2439	2.3151
50	35.26	35.01	12.68	12.81	0.4666	0.4611
51	11.11	10.89	-11.10	-10.90	0.4087	0.4243
52	16.27	16.03	-6.24	-5.99	0.4260	0.4353
53	21.11	20.88	-1.36	-1.11	0.4355	0.4418
54	26.19	25.95	3.70	3.96	0.4468	0.4489
55	31.29	31.04	8.77	9.03	0.4584	0.4561
56	41.10	40.85	18.62	18.88	0.4734	0.4681
57	46.15	45.89	23.68	23.95	0.4838	0.4747
58	51.26	50.99	28.73	29.00	0.4965	0.4842

(continued)

Table 1. (continued).

No	T_{hp} °C	T_h °C	T_{cp} °C	T_c °C	E_h mV	E_c mV
59	35.12	34.87	12.67	12.94	0.4639	0.4595
60	29.16	29.05	18.88	19.00	0.2130	0.2113
61	39.31	38.96	8.63	8.99	0.6343	0.6271
62	15.20	15.09	4.88	5.00	0.1962	0.2084
63	25.23	24.90	-5.40	-5.05	0.5999	0.5967
64	35.33	35.09	12.77	13.03	0.4523	0.4450
65	11.08	10.86	-11.39	-11.10	0.3990	0.4023
66	51.47	51.20	28.83	29.10	0.4862	0.4715
67	29.38	29.26	18.91	19.03	0.2093	0.2071
68	39.34	39.01	8.66	9.00	0.6103	0.6053
69	14.99	14.89	4.79	4.91	0.1859	0.1964
70	25.35	25.04	-5.29	-4.97	0.5791	0.5670
71	36.34	34.97	11.72	13.16	2.5485	2.5130
72	12.27	11.00	-12.30	-11.00	2.3268	2.2764
73	52.53	51.07	27.71	29.22	2.6840	2.7128
74	29.78	29.14	18.37	19.03	1.1818	1.1729
75	40.90	39.03	7.35	9.30	3.4774	3.4243
76	15.71	15.11	4.50	5.13	1.1003	1.0913
77	26.78	24.98	-6.87	-4.98	3.3361	3.2411
78	35.67	35.41	12.48	12.74	0.4820	0.4715
79	35.67	35.41	12.44	12.71	0.4856	0.4665
80	51.28	51.02	29.14	29.40	0.4990	0.4696
81	51.28	51.02	29.24	29.51	0.4856	0.4833
82	46.30	46.04	23.64	23.91	0.4886	0.4840
83	41.36	41.11	18.97	19.23	0.4759	0.4673
84	26.18	25.94	3.90	4.15	0.4422	0.4342
85	21.58	21.34	-0.97	-0.72	0.4371	0.4293
86	16.32	16.09	-6.26	-6.02	0.4271	0.4179
87	11.22	10.99	-11.25	-11.00	0.4159	0.4065
88	10.96	10.72	-11.27	-11.00	0.4232	0.4143
89	16.31	16.07	-6.11	-5.86	0.4351	0.4274
90	21.28	21.04	-1.10	-0.84	0.4413	0.4348
91	26.17	25.92	3.62	3.88	0.4559	0.4469

Table 2. Comparison of the steady state heat fluxes, Q_{ref} and Q , calculated according to the information derived from guarded hot plate apparatus measurements and according to the calibration method adopted in this work respectively.

No.	W/m ²		
	Q_{ref}	Q	% diff
1	4.995	4.965	-0.6
2	4.407	4.442	0.8
3	4.443	4.445	0.0
4	4.550	4.517	-0.7
5	4.656	4.624	-0.7
6	4.757	4.717	-0.8
7	4.890	4.851	-0.8
8	5.041	5.006	-0.7
9	5.143	5.106	-0.7
10	5.232	5.212	-0.4
11	2.207	2.180	-1.2
12	6.622	6.536	-1.3
13	2.118	2.102	-0.8
14	6.303	6.224	-1.3
15	10.384	10.363	-0.2
16	9.737	9.672	-0.7
17	9.987	9.945	-0.4
18	10.037	10.007	-0.3
19	10.206	10.164	-0.4
20	10.388	10.367	-0.2
21	10.817	10.809	-0.1
22	10.982	10.985	0.0
23	11.174	11.201	0.2
24	10.552	10.551	-0.0
25	4.779	4.785	0.1
26	14.368	14.339	-0.2
27	4.546	4.551	0.1
28	13.648	13.636	-0.1
29	13.551	13.443	-0.8

(continued)

Table 2. (continued).

No.	W/m ²		
	Q_{ref}	Q	% diff
30	12.287	12.224	-0.5
31	12.601	12.535	-0.5
32	12.952	12.904	-0.4
33	13.072	13.014	-0.4
34	13.335	13.261	-0.6
35	13.956	13.848	-0.8
36	14.167	14.080	-0.6
37	14.590	14.515	-0.5
38	13.422	13.399	-0.2
39	6.085	6.102	0.3
40	18.236	18.213	-0.1
41	5.815	5.840	0.4
42	17.572	17.640	0.4
43	6.081	6.118	0.6
44	9.235	9.286	0.6
45	12.319	12.371	0.4
46	15.439	15.496	0.4
47	18.567	18.590	0.1
48	21.582	21.584	0.0
49	24.659	24.193	-1.9
50	4.922	4.923	0.0
51	4.480	4.444	-0.8
52	4.599	4.590	-0.2
53	4.661	4.670	0.2
54	4.737	4.763	0.5
55	4.819	4.857	0.8
56	4.966	4.990	0.5
57	5.047	5.074	0.5
58	5.147	5.186	0.8
59	4.864	4.900	0.8
60	2.229	2.252	1.0
61	6.647	6.694	0.7

(continued)

Table 2. (continued).

No.	W/m ²		% diff
	Q_{ref}	Q	
62	2.141	2.154	0.6
63	6.352	6.370	0.3
64	4.712	4.762	1.0
65	4.222	4.275	1.3
66	5.037	5.064	0.5
67	2.186	2.210	1.1
68	6.408	6.451	0.7
69	2.007	2.035	1.4
70	6.036	6.101	1.1
71	27.305	26.860	-1.6
72	25.054	24.558	-2.0
73	29.272	28.537	-2.5
74	12.655	12.496	-1.3
75	37.219	36.625	-1.6
76	11.818	11.666	-1.3
77	35.445	35.012	-1.2
78	4.995	5.060	1.3
79	5.003	5.053	1.0
80	5.097	5.122	0.5
81	5.072	5.123	1.0
82	5.106	5.149	0.8
83	4.948	4.999	1.0
84	4.615	4.660	1.0
85	4.572	4.612	0.9
86	4.470	4.503	0.7
87	4.339	4.388	1.1
88	4.465	4.468	0.1
89	4.580	4.596	0.4
90	4.642	4.664	0.5
91	4.748	4.801	1.1

FIGURE 2. The dependence between reference heat flux, Q_{ref} and the transducer output from the plates.

FIGURE 3. The "sensitivity" of each plate calculated as $(Q_{ref}/\text{transducer output})$ for both plates.

FIGURE 4. The average "sensitivity" of the apparatus calculated as $(Q_{ref}/\text{the average of the two transducer outputs})$.

tribution. Are there other factors that should be considered in the calibration? To answer this question the influence of the four temperatures, measured in each set, on S was next investigated. An average temperature T_{avg} was defined as:

$$T_{avg} = \frac{T_{hp} + T_h + T_{cp} + T_c}{4} \quad (4)$$

The relation between T_{avg} and S for the 91 measurements are shown in Figure 5. A trend, though concealed by the scatter, emerges from Figure 5. This becomes more clear when the data are reduced as follows. In Figure 5, nine separate "bins" can be identified. Each bin corresponds to one T_{avg} . Now each bin is averaged for the temperature and the sensitivity factor. The results from this data reduction are shown in Figure 6. It can be seen that for

FIGURE 5. The dependence of the average sensitivity on the average transducer temperature (see text, Equation [4]).

FIGURE 6. Results from data reduction by "bin" averaging (see text).

the range of temperatures, 0 to 40°C a very small but measureable temperature coefficient for S can be introduced. From a linear regression analysis:

$$S = S_0 + S_1 T_{avg} \quad (5)$$

where

$$S_0 = 10.67 \pm 0.01 \text{ W/(m}^2 \cdot \text{mV)}$$

$$S_1 = 0.00235 \pm 0.00030 \text{ W/(m}^2 \cdot \text{mV} \cdot ^\circ\text{C)}$$

Then, for the heat flow meter used in this work the steady state heat flux, $Q(\text{W/m}^2)$, would be given by:

$$Q = (S_0 + S_1 T_{avg}) E_{avg} \quad (6)$$

This equation was used to calculate Q for all the measurements reported in Table 1. These calculated values are compared with Q_{ref} in Table 2. The percentage difference between the two are plotted in Figure 7. It can be seen that 90 out of the 91 measurements correspond to Q_{ref} within 2%; with the majority of them within 1.5%, for the most part of the heat flux range investigated here the distribution of the percentage difference is even. The only bias seen is with the six values at the higher end of the range. But in spite of this bias, Equation (6) gives acceptable values for the steady state heat flux for all the measurements reported here.

CONCLUDING REMARKS

The calibration measurements reported here included transfer standards with thicknesses between 26 and 158 mm, mean specimen temperature be-

FIGURE 7. Comparison between Q_{ref} and that calculated using the calibration method.

tween 0 and 40°C, temperature differences between 10 and 40 K and two types of insulating materials. The results show that the specimen thickness, the mean specimen temperature, the magnitude of the temperature differential across the test specimen and even difference in the material did not significantly influence the calibration procedure adopted for the heat flow meter described here. The steady state heat flux determined in this apparatus should match within 2% of that determined using a guarded hot plate apparatus. The calibration method described here was also successfully applied to two other heat flow meter apparatuses in our laboratory.

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