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A STUDY OF THE EFFECTS OF EDGE INSULATION AND AMBIENT TEMPERATURES ON ERRORS IN GUARDED HOT-PLATE MEASUREMENTS

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ÉTUDE DES EFFETS DE L'ISOLEMENT DES ARÊTES ET DE LA TEMPÉRATURE AMBIANTE SUR LES ERREURS DE MESURES À LA PLAQUE CHAUFFANTE PROTÉGÉE

SOMMAIRE

Les erreurs de mesures à la plaque chauffante protégée (guarded hot plate) causées par l'action des arêtes limite l'épaisseur des éprouvettes à l'essai au tiers environ des dimensions de la partie centrale de l'appareil de chauffage. L'auteur a essayé des échantillons de conductibilité connue en employant diverses épaisseurs d'isolant aux arêtes des éprouvettes et différentes températures ambiantes. Il a trouvé qu'il était possible de déterminer les dispositions les plus favorables pour que les erreurs dues à l'action des arêtes soient négligeables pour les éprouvettes les plus épaisses.

A Study of the Effects of Edge Insulation and Ambient Temperatures On Errors in Guarded Hot-Plate Measurements

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The error due to edge effects of the guarded hot-plate apparatus has limited the thickness of specimens that may be tested to approximately one third the dimension of the central section of the heating unit. Samples of known conductivity were tested using various thicknesses of edge insulation and various ambient temperatures. It was found possible to determine the optimum edge conditions so that errors due to edge effects are negligible for very thick specimens.

Key Words: Conductivity, errors, guarded hot-plate, heat conduction, standard test, thermal conductivity, thermal insulation.

1. Introduction

The most widely used and precise method of determining thermal conductivity is with the guarded hot-plate and a standard method using this equipment has been adopted by ASTM (1)[1]. This method of test limits the thickness of specimen to one third the linear dimension of the heating unit. In order to test thick specimens using this method, guarded hot-plates with proportionately large dimensions are required. Another approach is to slice the material and produce a number of thinner specimens that may be tested in a smaller guarded hot-plate. A third approach is to test thick specimens in a small guarded hot-plate apparatus and reduce errors due to edge effects by control of the boundary conditions.

Each of the three methods has its limitations. A large hot-plate is expensive, difficult to build and operate, and not suitable for the majority of specimens. Because of this many laboratories are unlikely to have one. Slicing samples to make specimens thin for testing in smaller guarded hot-plates is not always convenient or desirable and testing thick specimens in small plates can result in large errors due to edge effects. An experimental program was proposed to evaluate the possibility of reducing edge errors so that thick specimens can be tested on small guarded hot-plates.

The guarded hot-plate method for measurement of thermal conductivity is based on the assumption that isotherms in the central area of the test specimens are planes parallel to the hot and cold-plates, i.e., that the heat flow is perpendicular to the faces of the sample. This assumption of one-directional heat flow is valid only for thin specimens unless the edge of the sample has a temperature profile that is nearly the same as that at the centerline of the sample. The normal procedure for the guarded hot-plate is to limit the heat gained or lost from the edge of the sample by using edge insulation, by maintaining the ambient temperature at an appropriate level (2), and by limiting the thickness of the specimen (3) so that errors due to edge effects are negligible.

With thick specimens the isotherms become distorted if heat is allowed to enter and/or leave the edge of the specimens. This may result in an erroneous measurement of thermal conductivity if the edge conditions are not carefully controlled. If the ambient temperature is much above the sample temperature, heat will flow into the edge of the specimen, distorting the isotherms and making the

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[1] Figures in brackets indicate the literature references at the end of this paper.

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apparent thermal conductivity low. An ambient temperature much below the sample temperature will give the opposite effect. It would appear, therefore, that there is some optimum temperature that will give a minimum error. Since the apparent thermal conductivity is affected by heat entering or leaving the edge of the specimen, edge insulation should help to reduce the flow of heat and consequently reduce the error in the thermal conductivity.

The object of the experimental work reported in this paper was to determine the effectiveness of using edge insulation and of controlling ambient temperature in reducing errors when measuring the thermal conductivity of thick specimens.

2. Experimental

2.1 Equipment

The guarded hot-plate equipment used for the tests was similar to one designed by the National Bureau of Standards in Washington (4). The test area is 10 cm square with a 5-cm-wide guard area that is automatically kept at the same temperature as the test area. The hot-plate was operated in a horizontal position in an insulated box. The temperature in the box was controlled by circulating fluid at a controlled temperature through heat exchanger plates that covered three walls of the box. The air in the box was stirred with a large-diameter, low-speed propeller fan.

2.2 Specimens

Polyurethane foam and silicone rubber were used to make up the samples for test. Thick samples were made by stacking homogeneous material in slices 13 mm to 19 mm thick. The actual thermal conductivity was determined by adding the previously determined resistances of pairs of slices and converting the total resistance to thermal conductivity. The resistance of each pair of slices was determined in two guarded hot-plates, in the plate used for the thick specimens, and in a plate of the same size, similar in design to one developed at the University of Saskatchewan and described by Woodside and Wilson (5). The values obtained with the two guarded hot-plates had a maximum deviation of 0.06 per cent and a mean deviation 0.03 per cent for the polyurethane foam samples and 0.46 per cent and 0.21 per cent respectively for the silicone rubber.

2.3 Method

The first series of tests was carried out to check the effect of varying the thickness of edge insulation. Specimens of polyurethane foam and silicone rubber 85 mm thick were used for these tests. The ambient temperature was controlled close to the mean temperature of the sample 24 C; the temperature difference across the sample was maintained at 22 C. A series of tests was run starting with no edge insulation and applying 13 mm, 25 mm, 51 mm, and 76 mm of edge insulation to the edge of the specimen covering the hot-plate completely and extending 20 mm beyond the faces of the cold-plates. The test was repeated with an ambient temperature of 38 C; all other conditions remained the same. The edge insulation had a thermal conductivity approximately equal to the specimen. The polyurethane samples had edge insulation of polyurethane with a $\lambda = 0.0230$ W $m^{-1}deg^{-1}$ while the silicone rubber samples had neoprene rubber for the edge insulation with a $\lambda = 0.304$. After the completion of these two series an approximate optimum ambient temperature for minimum error was determined by a linear interpolation of the previous results and a third series was run using this ambient temperature. The results of these three tests are given in Table 1 for polyurethane foam and in Table 2 for silicone rubber. The ambient temperature has been converted to a nondimensional temperature index (ATI) by relating it to the temperatures of the hot- and cold-plate, i.e. ATI = $(T_a - T_c) / (T_h - T_c)$. Where T_a is the ambient temperature and T_h and T_c are hot- and cold-plate temperatures respectively.

2.4 Results

The results shown in Tables 1 and 2 have been plotted in figures 1 and 2. The error in thermal conductivity has been plotted against the thickness of edge insulation for corrected ATI. For each thickness of edge insulation the best straightline fit was used to determine the optimum ATI for minimum error and to correct the ATI to 0.5, 1.10, and a value near the optimum for plotting. The values of optimum ATI have been plotted against the thickness of edge insulation in figures 3 and 4.

Table 1 Experimental values of error in thermal conductivity measurements for 85.05 mm polyurethane foam samples

Polyurethane foam samples: $\lambda = 0.230_4$, $d = 31.89$;

NBS guarded hot-plate, in a horizontal configuration:
203.2 mm x 203.2 mm, test area 101.6 mm x 101.6 mm.

Edge Insulation thickness, mm	Mean Temperature, °C	Temperature Difference, °C	Ambient Temperature Index	Error, per cent
		Series 1		
0	23.89	22.26	0.479	6.4
12.7	24.12	22.86	0.479	3.5
25.4	24.19	22.94	0.476	2.8
50.8	24.28	23.16	0.508	1.7
76.2	24.34	23.21	0.502	1.5
		Series 2		
0	23.91	22.11	1.103	-27.65
12.7	24.25	22.99	1.100	-16.26
25.4	24.13	22.77	1.121	-13.27
50.8	24.39	23.16	1.081	-7.84
76.2	24.18	22.78	1.098	-6.33
		Series 3		
0	24.08	22.56	0.649	-0.6
12.7	24.08	22.61	0.646	-0.7
25.4	24.12	22.28	0.668	-2.2
50.8	24.29	23.14	0.631	0.1
76.2	24.23	23.12	0.626	0.2

The ambient temperature for minimum error is between the mean temperature of the sample and the temperature of the hot-plate. This is the expected result for a guarded hot-plate where the heat is metered at the hot-plate side. If the heat is metered at the cold-plate side the optimum ambient temperature would be between the mean and cold-plate temperatures. When the ATI is not the optimum, edge insulation reduces the error as expected. With thick edge insulations the ambient temperature is not as critical. The optimum ATI appears to be a linear function of the edge insulation thickness. Thicker edge insulation requires a higher optimum ATI. Specimens of high thermal conductivity require higher ATI for minimum error for all thickness of edge insulation.

Using the results of these series of tests an attempt was made to see how thick the specimens could be made and still maintain a reasonable degree of accuracy. The thickness of polyurethane foam specimens was varied from 75 mm to 189 mm while the edge insulation thickness was kept constant at 57 mm and the ATI was near optimum as determined in the first series. As specimen thickness was increased, the measured error was larger than expected when compared with the tests done with 85-mm samples. This would seem to indicate that the optimum ATI is also a function of specimen thickness. The results are shown in Table 3.

3. Conclusion

The error due to the edge effects of the guarded hot-plate may be reduced with edge insulation but only becomes zero when the ambient temperature is at one specific value. The optimum ATI appears

Table 2 Experimental values of error in thermal conductivity measurements for 84.46 mm silicone rubber samples

Silicone rubber samples: $\lambda = 0.246_9$, d = 1190 kg/m^3

Neoprene rubber edge insulation: $\lambda = 0.304$, d = 1400 kg/m^3

NBS guarded hot-plate, in a horizontal configuration: 203.2 mm sq, test area 101.6 mm sq

Edge Insulation thickness, mm	Mean Temperature, °C	Temperature Difference °C	Ambient Temperature Index	Error, per cent
		Series 1		
0	23.87	22.12	0.508	3.62
12.7	23.89	22.10	0.499	3.28
25.4	24.01	22.24	0.502	3.22
50.8	23.94	22.10	0.512	3.31
76.2	23.82	22.08	0.500	3.86
		Series 2		
0	23.82	21.94	1.150	-18.4
12.7	23.75	22.17	1.127	-12.32
25.4	23.99	22.17	1.164	-10.49
50.8	23.93	22.07	1.166	-6.32
76.2	23.84	21.99	1.150	-4.46
		Series 3		
0	24.02	22.52	0.604	0.18
12.7	23.89	22.25	0.603	0.77
25.4	23.92	22.11	0.608	0.97
50.8	23.92	22.05	0.600	2.07
76.2	23.83	22.07	0.610	2.14

Table 3 Experimental values of error in thermal conductivity measurements for polyurethane foam samples tested in an NBS 203.2 mm x 203.2 mm guarded hot-plate using 57 mm of polyurethane foam edge insulation

Sample Thickness, mm	Mean Temperature, °C	Temperature Difference, °C	Ambient Temperature Index	Error, per cent
75.29	23.91	22.25	0.647	-1.0
75.25	23.93	22.26	0.596	-0.6
75.25	23.92	22.21	0.618	-1.4
75.25	23.87	22.12	0.666	-1.9
75.25	23.95	22.25	0.680	-1.8
75.25	23.89	22.14	0.619	-1.4
75.25	23.88	22.13	0.594	-0.9
94.06	23.93	22.28	0.661	-2.4
112.89	23.85	22.14	0.659	-3.5
112.85	23.96	22.26	0.594	-3.0
112.85	23.93	22.24	0.585	-2.3
131.68	23.89	22.24	0.660	-4.0
150.47	23.91	22.28	0.628	-5.0
150.42	23.92	22.26	0.569	0.4
150.42	23.90	22.21	0.564	0.2
150.42	23.89	22.16	0.568	0.3
150.42	23.92	22.22	0.598	-2.1
150.42	23.89	22.17	0.597	-1.9
150.42	23.89	22.17	0.602	-3.1
169.24	23.97	22.40	0.625	-4.1
169.23	23.86	22.16	0.643	-6.7
169.23	23.92	22.25	0.628	-6.4
169.23	23.80	22.01	0.627	-5.4

to be a function of the edge insulation thickness, sample thermal conductivity, and thickness.

In the work reported here the edge insulation had a thermal conductivity the same as the sample. Edge insulation with a thermal conductivity lower than the sample will probably reduce the error due to edge effects, but the optimum ATI will doubtless change.

This paper deals mainly with a sample thickness that is 0.84 times the linear dimension of the central area of the hot-plate. From the values of error obtained with much thicker samples it appears that different values of specimen thickness have different values for the optimum ambient temperature index.

It would appear that samples that are as thick as the width of the central area of the hot-plate may be tested with little additional error provided edge insulation is used and the ambient temperature is maintained at the optimum value. More experience is needed, however, before thick specimens can be tested with assurance that errors due to edge effects have been eliminated. It should be noted that homogeneous samples were used in this study and the results are not necessarily applicable to non-homogeneous specimens.

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4. References

(1) Method of Test for Thermal Conductivity of Materials by Means of the Guarded Hot-Plate (C177 - 63), 1966 Book of ASTM Standards, Part 14, p.17.

(2) Ibid, Paragraph 4(k) p.22.

(3) Ibid, Paragraph 6(a) p.25.

(4) Ibid, Note 1, p.17.

(5) Woodside, W. and Wilson, A.G. Unbalance errors in guarded hot-plate measurements. In Symposium on Thermal Conductivity Measurements and Applications of Thermal Insulations, A.S.T.M. Special Technical Publication No. 217, p.32-46 (1957).

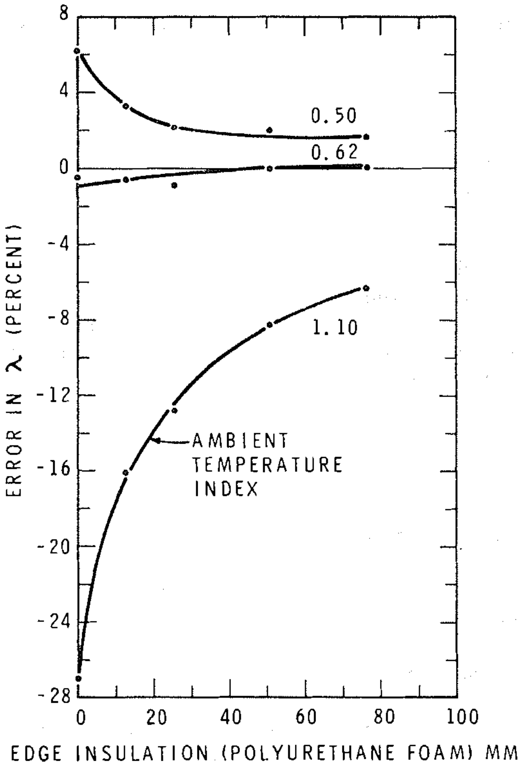

Figure 1. Error in λ vs edge insulation thickness showing effect of ambient temperature indexes for 85 mm samples of polyurethane foam.

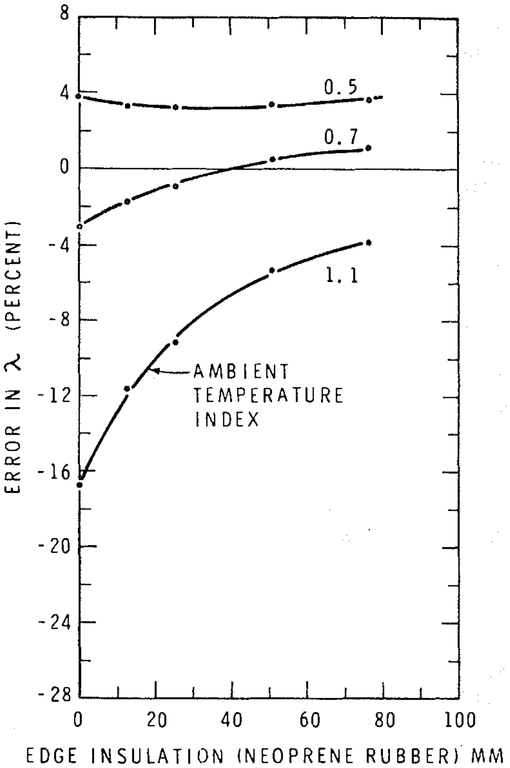

Figure 2. Error in λ vs edge insulation thickness showing effect of ambient temperature indexes for 85 mm samples of silicone rubber.

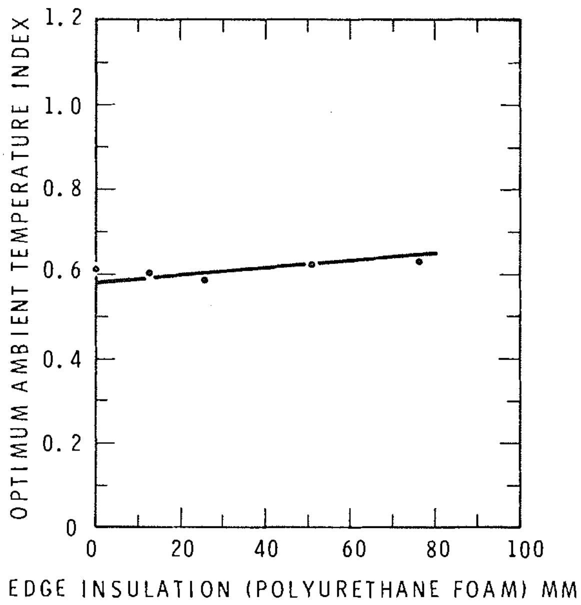

Figure 3. Optimum ambient temperature index vs edge insulation thickness for 85 mm samples of polyurethane foam.

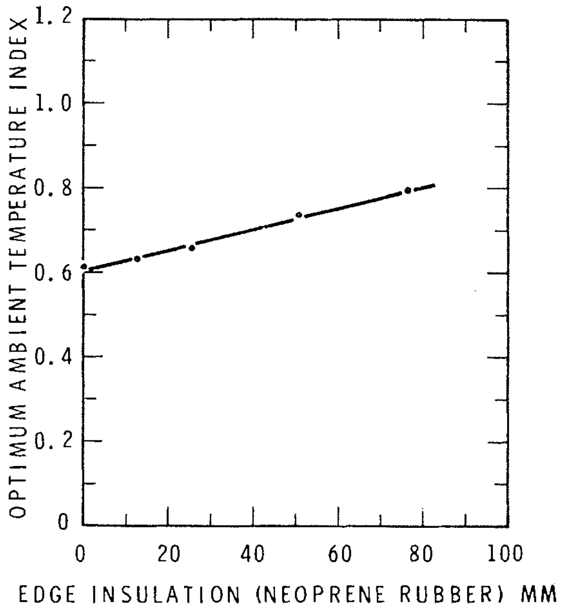

Figure 4. Optimum ambient temperature index vs edge insulation thickness for 85 mm samples of silicone rubber.