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A PRESSURE-VOLUME APPARATUS TO MEASURE THE EFFECTIVE THICKNESS OF CELLULAR PLASTIC TEST SPECIMENS

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Abstract:

Thin specimens of cellular plastic insulations are used in thermal resistance and gas diffusion property measurements. It is known that several cells on the surfaces of the test specimens are destroyed during specimen preparation. Hence the effective thickness of the test specimen differs from the geometrical thickness and proper corrections are to be made for the thickness of the destroyed surface layers before other properties are calculated.

This note presents an apparatus, its operating principles and an experimental procedure to determine the thickness of destroyed surface layers of cellular plastic insulation test specimens.

A PRESSURE-VOLUME APPARATUS TO MEASURE THE EFFECTIVE THICKNESS OF CELLULAR PLASTIC TEST SPECIMENS

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Introduction:

At the Institute for Research in Construction, investigations on the long-term thermal performance of spray foam insulations have resulted in a test methodology(1-3) that involves thermal testing of thin slices of foam products. In this methodology, foam samples of 50 or 100 mm thickness are sliced into several thinner, 5 or 10 mm thick, specimens and tested simultaneously in heat flow meter apparatuses. To use the information from the heat flow meter apparatus for subsequently predicting the long term behaviour of the original foam sample, one has to know the effective diffusion thickness across the test specimens. This thickness differs from the geometrical thickness because during the slicing process several cells on the surface layer are damaged. Hence an apparatus was developed(4) to estimate the thickness of the destroyed surface layer. This note describes the pressure-volume relations that form the basis of the measurements and presents a brief description of the apparatus, the methods for calibration and few test results. The test results are included only to introduce the experimental procedure and hence they will not be interpreted.

The Pressure Volume Relations:

Assume that two volumes V_1 and V_2 are separated through a valve and filled with a gas at pressure P_o at the same temperature T . Now let us introduce a solid material of volume V within V_2 and increase the pressure in the volume V_1 to P_i by introducing more of the gas. Next, let us open the valve between V_1 and V_2 and let the pressure of the gas attain the uniform value P_f . All these are done under isothermal conditions. These steps are shown schematically in Figure 1.

Using ideal gas equation it can be shown that,

$$V_1 \cdot (P_i - P_o) = (V_1 + V_2 - V) \cdot (P_f - P_o) \quad (1)$$

Equation (1) can be rewritten as

$$V = V_2 - V_1 \cdot (P_1 - P_2) / P_2 \quad (2)$$

where,

$$P_1 = (P_i - P_o) \text{ and } P_2 = (P_f - P_o)$$

According to equation (2), if the volumes V_1 and V_2 are known and if the quantities P_1 and P_2 are measured the volume V of the solid can be calculated; if the solid material used in these measurements happens to be a specimen of a cellular plastic insulation, V corresponds to the volume occupied by closed cells in the solid matrix. The measurements needed can be carried out fast for a relatively low value (100 Pa) for P_1 and hence any effect due to gas diffusion into the specimen is negligible.

The Apparatus:

The experimental setup in which the above relation is applied is shown schematically in Figure 2. It consists of two cylindrical chambers, called the source chamber (C1) and the specimen chamber (C2), connected through a copper tubing, but separated by a toggle valve (T2). The specimen chamber has a removable lid which can be screwed on to the cylinder air tight; an O-ring, placed in a groove between the lid and the cylinder provides a good seal. The copper tubing, on the source chamber side, carries a calibrated differential pressure transducer (DP) together with a digital read-out system. The source chamber is provided with an additional valve (T1).

The volume between T1 and T2, inclusive of the connections to the pressure transducer, corresponds to V_1 in equation (1) and the volume of C2 up to T2 corresponds to V_2 .

Experimental Procedure:

In any set of measurements the steps listed below are followed.

1. the digital read-out system on the pressure transducer, DP, is turned on.
2. the lid of the specimen chamber, C2, is opened.
3. the specimen of effective volume V is placed in the specimen chamber.
4. the lid of the specimen chamber is put back and all the screws on the lid are tightened.
5. the valves T1 and T2 are opened to leave the setup open to atmosphere. Then the digital read-out should show 0; in other words the initial uniform pressure P_0 equals to atmospheric pressure.
6. the valve T2 is closed. The digital read-out still should show 0. (For protection to DP transducer T1 should also be closed.)
7. the gas (oxygen, nitrogen or air) is admitted from a gas cylinder into the source chamber C1, by very slowly opening T1 to get a reading in the vicinity of 100.0 Pa on the digital read-out. T1 is closed. The read-out, once a steady value, P_1 , is attained, is recorded.
8. T2 is opened and the new steady value, P_2 , from the read-out is recorded.
9. the operations from step 5 to 8 are repeated at least five times. (A three-way valve between T1 and the gas cylinder makes the repetition easier.)

Calibration of the Apparatus:

The calibration involves the determination of the volumes V_1 and V_2 in equations (1) and (2). It is better to do this calibration after the assembly of the equipment is complete rather than to determine each volume element separately before assembly, as was done earlier (4). This is a rather straight forward measurement.

Two metallic discs were machined and from direct measurements their volumes were determined to be 250.3 cm^3 and 432.3 cm^3 . These discs are referred to as the brass disc and the aluminum discs respectively. The discs, one at a time, were placed in the specimen chamber and the ratio $(P_1 - P_2) / P_2$ was determined for each using the experimental procedure described above. The results from these measurements are listed in Table 1. Substitution of these ratios and the directly measured volumes of the discs in equation (2) results in two simultaneous equations which were solved for the volumes V_1 and V_2 . For the apparatus at the Institute for Research in Construction these volumes are 954.8 cm^3 and 623.2 cm^3 respectively. The error in these measurements is estimated to be less than 1 %.

Determination of the thickness of the destroyed surface layer of cellular plastic test specimens:

Four samples of cellular plastic insulations were chosen for the measurements. These were:

- an extruded polystyrene foam
- a polyurethane spray foam
- a polyisocyanurate foam and
- a phenolic foam.

These samples were sliced to give layers of approximate thickness of 5 mm in the same way specimens are prepared for thermal resistance testing. From these slices three or four circular specimens (diameter approximately equal to 15 cm) were cut. The edge of each specimen was coated with an epoxy resin to make the edge impermeable to the test gas (sealing of the edge is particularly important if the specimens are to be subsequently used for gas diffusion measurements; if the edge is not coated, then the surface area of the specimens due to the exposed edges are to be included in the calculation of the thickness of the destroyed surface layers). Their geometrical volumes were determined by direct measurements of thickness and diameter. They were then arranged as a stack to be placed in the specimen chamber of the pressure-volume apparatus. The effective volume of the stack of specimens is then determined according to the procedure described above. The results from such measurements on the specimens from the four samples are listed in Table 2.

From the value of $(P_1 - P_2) / P_2$, the effective volume of each stack was calculated according to equation(2). The geometrical volume being known, the volume of the destroyed surface layer was calculated as the difference between the geometrical volume and the effective volume. This difference divided by the total surface area of all the specimens(excluding the edge) gave the thickness of the destroyed surface layer. These results are summarized in Table 3.

Table 1: Experimental Results from the Calibration Measurements

P ₁ , Pa	P ₂ , Pa	(P ₁ - P ₂)/P ₂
Aluminum Disc V = 432.3 cm ³		
89.86	48.90	0.8378
88.68	48.21	0.8395
77.93	42.42	0.8369
98.04	53.27	0.8405
84.06	45.78	0.8363
97.54	53.02	0.8398
87.85	47.74	0.8402
99.75	54.26	0.8385
86.67	47.18	0.8372
76.09	41.37	0.8391
84.76	46.15	0.8367
	Average	0.8384
Brass Disc, V = 250.3 cm ³		
95.78	44.94	1.131
97.93	45.97	1.130
80.08	37.65	1.127
80.71	37.87	1.131
77.60	36.36	1.134
81.39	38.27	1.127
90.10	42.30	1.130
86.94	40.83	1.129
84.56	39.70	1.130
93.83	43.99	1.133
88.36	41.44	1.132
	Average	1.130

Concluding Remarks:

The principle used here is well known and is applied in commercial air pyknometers. The main differences between such commercial instruments and the procedure presented here are in the size of the test specimens used and the magnitude of the pressure applied. While commercial equipment uses $(2.5\text{ cm})^3$, in the apparatus described here, the size of test specimens is comparable to those used in thermal resistance tests - especially the surface area involved in the two types of measurements. The pressure applied is about 100 Pa, whereas in commercial pyrometers it is of the order of 50 kPa. Construction, installation and calibration of the apparatus as well as measurements involve only basic technical skills and hence can be easily adapted in any industrial laboratory. Though it is associated with slicing and thermal testing, the apparatus finds application in gas diffusion measurements(4). It can also be used to investigate the damage done to the cellular structure during specimen preparation or as the foam ages or as the foam is subjected to various exposures such as high temperature or humidity and thermal gradients.

Table 2. Experimental data on the specimens of cellular plastic insulations.

P ₁ , Pa	P ₂ , Pa	(P ₁ -P ₂)/P ₂
Extruded Polystyrene		
98.02	49.77	0.970
78.6	39.96	0.967
82.02	41.69	0.967
89.41	45.42	0.968
96.1	48.81	0.969
98.42	49.98	0.969
85.9	43.53	0.973
93.63	47.55	0.969
89.81	45.69	0.966
83.26	42.28	0.969
	Average	0.969
Polyurethane		
92.8	45.3	1.049
92.9	45.3	1.051
95	46.3	1.052
85.5	41.6	1.055
83.5	40.6	1.057
82.7	40.2	1.057
89.1	43.4	1.053
88	42.7	1.061
85.4	41.6	1.053
	Average	1.054
Polyisocyanurate		
98.3	50.43	0.949
89.99	46.35	0.942
92.26	47.47	0.944
81.6	41.92	0.946
84.09	43.18	0.947
74.21	38.19	0.943
86.12	44.2	0.948
85.12	43.73	0.947
93.4	47.97	0.947
	Average	0.946
Phenolic Foam		
96.0	46.4	1.079
84.8	41.0	1.075
93.1	45.0	1.078
82.1	39.6	1.079
76.8	37.1	1.075
86.8	42.0	1.074
86.2	41.7	1.074
92.9	45.0	1.073
91.7	44.4	1.074
	Average	1.076

Table 3. Thickness of destroyed surface layer (TDSL).

Sample	Effective Volume (cm ³)	Geometrical Volume (cm ³)	Area (cm ²)	TDSL (per 1 surface) mm
Extruded Polystyrene	351	371.6	700.9	0.15
Polyurethane	298	368.6	688.8	0.51
Polyisocyanurate	365	396.2	707.5	0.22
Phenolic	284	320.9	507.3	0.36

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Figure 1. Schematics of the pressure-volume operations

Figure 2. Schematics of the pressure-volume apparatus