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Specific Heat Capacity and Thermal Conductivity of Foam Glass (Type 150P) at Temperatures from 80 to 400 K[1]

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Low-temperature specific heat capacities of foam glass (Type 150P) have been measured from 79 to 395 K by a precision automated adiabatic calorimeter. Thermal conductivities of the glass foams have been determined from 243 to 395 K with a flat steady-state heat-flow meter. Experimental results have shown that both the specific heat capacities and thermal conductivities of the 150P foam glass increased with temperature. Experimentally measured specific heat capacities have been fitted by a polynomial equation from 79 to 395 K: $C_p/\mathrm{J}\cdot\mathrm{g}^{-1}\cdot\mathrm{K}^{-1} = 0.6889 + 0.3332x - 0.0578x^2 + 0.0987x^3 + 0.0521x^4 - 0.0330x^5 - 0.0629x^6$, where $x = (T/\mathrm{K} - 273)/158$. Experimental thermal conductivities as a function of temperature (T) have been fitted by another polynomial equation from 243 to 395 K: $\lambda/\ \mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1} = 0.14433 + 0.00129T - 2.834 \times 10^{-6}T^2 + 2.18 \times 10^{-9}T^3$. In addition, thermal diffusivities (a) of the form glass sample were calculated from the specific heat capacities and thermal conductivities and have been fitted by a polynomial equation as a function of temperature (T): $a/\mathrm{m}^2\cdot\mathrm{s}^{-1} = -1.68285 + 0.01833T - 5.84891 \times 10^{-5}T^2 + 8.11942 \times 10^{-8}T^3 - 4.24975 \times 10^{-11}T^4$.

KEY WORDS: enthalpy and entropy functions; foam glass; low-temperature specific heat capacity; thermal conductivity; thermal diffusivity.

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1. INTRODUCTION

Foam glass [1–3] is a heat-preservation and heat-insulation material used in the building industry. It is produced by using waste glass and powdered coal ash (fly-ash) as the primary crude materials; pumice stone, carbon black, and sodium carbonate as the auxiliary materials; and by adding various additives, such as sodium fluorosilicate, boric acid, and sodium hexametaphosphate. It is a porous glassy material full of well-proportioned bubbles. This foam glass has been produced by a series of processes such as fusion of the mixed crude materials, and foaming, annealing, and cooling in a special mold. Foam glass has some advantages of robustness, durability, safety, reliability, and resistance to chemical corrosion, and it is not vulnerable to attacks by pests (ants, rats, etc.). This material is water-proof and has a low density, high mechanical strength, and good sound absorption properties.

The material has been widely used in many fields of heat preservation and heat insulation in the inner and outer walls of buildings, decoration engineering, petroleum chemical engineering, refrigeration, ground engineering, etc. Besides its application as a building material, many new uses for this foam glass have been found and the demand for it has greatly increased. For the purpose of the new applications of foam glass, thermodynamic data of the material, such as the specific heat capacity at temperatures below 400 K, thermodynamic functions (enthalpy and entropy), and thermal conductivity, are urgently needed. However, until now, these data have not been reported in the literature. In the present study, low-temperature specific heat capacities of a self-made foam glass (Type 150P) were measured in the temperature range from 79 to 395 K by a precision automated adiabatic calorimeter. Thermal conductivities of the foam glass were determined from 243 to 395 K with a flat steady-state heat-flow meter. Specific heat capacities were fitted by a polynomial function with the term $x = (T/\mathrm{K} - 273)/158$ in the experimental temperature range of 79–395 K. Thermal conductivities as a function of temperature (T) were fitted by another polynomial function from 243 to 395 K. In addition, thermal diffusivities (a) of the foam glass (Type 150P) were calculated based on the results of the specific heat capacities and thermal conductivities, and a polynomial function of the thermal diffusivities (a) versus temperature (T) was fitted.

2. EXPERIMENTAL

2.1. Sample

The foam glass used in these experiments was produced by Pengfei Heat-Preservation and Heat-Insulation Co. Ltd., Lanzhou, P. R. China. It

Table I. Chemical Components of the Primary Crude Materials used for Foam Glass 150 P

Crude materials	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	$K_2O + Na_2O$	H_2O
Powdered fly-ash (%)	58.11	25.60	2.20	0.51	3.90	6.98	2.70
Glass powder (%)	74.10	3.28	4.65	1.13	0.02	16.00	0.82

was prepared by a method given in the literature [1]. The chemical components of the primary crude materials are tabulated in Table I. The chemical composition of the solid material phase (glass phase) in the foam glass is as follows: SiO_2—71.7%, Al_2O_3—2.8%, (CaO + MgO)—11.5%, Fe_2O_3—0.2% and other—13.8%. The bubble sizes of the prepared foam glass are 1–3 mm. The porosity of the sample is about 90%. The density of the foam glass material was determined to be 142 $kg \cdot m^{-3}$ at 298.15 K.

2.2. Adiabatic Calorimetry

A high-precision automated adiabatic calorimeter [4, 5] was used to measure the specific heat capacities over the temperature range from 79 to 395 K. The thermometer was calibrated on the basis of ITS-90 by the Station of Low-temperature Metrology and Measurements, Academia Sinica.

Heat-capacity measurements were continuously and automatically carried out by means of the standard method of intermittently heating the sample and alternately measuring the temperature. The heating duration was 10 min, the equilibrated duration after the heating of the sample was 5 min and the temperature drift rates of the sample cell measured in an equilibrium period were always maintained within (10^{-3} to 10^{-4}) $K \cdot min^{-1}$ during the acquisition of heat-capacity data. The heating rate and temperature increments for each heat-capacity measurement point were generally controlled at, respectively, (0.1–0.3) $K \cdot min^{-1}$ and (1–3) K. The sample mass used for calorimetric measurements was 4.3511 g.

2.3. Measurement of Thermal Conductivity

A flat steady-state heat-flow meter (Model HFM-MR) was used to measure the thermal conductivity of the foam glass according to the method described in the literature [1] and the Chinese National Standard: GB 10295 [8]. One-dimensional constant heat flow similar to that existing in a large-area flat plate was established in the uniform plate-like test specimen with a flat surface during the measurement of thermal conductivity. One-dimensional constant heat flux (q) across the specimen and the

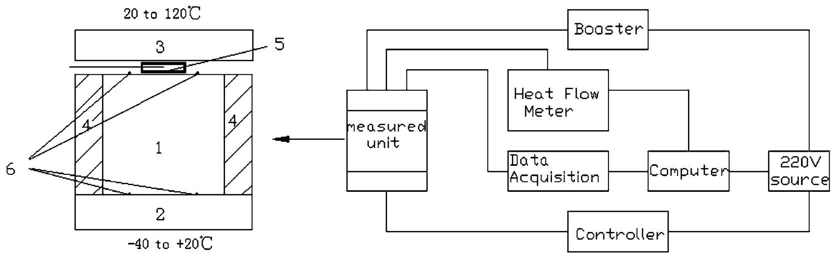

Fig. 1. Schematic diagram of the thermal conductivity measurement device: 1—measured material; 2—heat sink; 3—heat source; 4—thermal insulation material; 5—sensor of heat flow; 6—thermocouples.

temperature difference (ΔT) between the cold and hot surfaces were measured under steady-state conditions, and the thermal conductivity of the specimen can be calculated using the formula, $\lambda = q/\Delta T$.

The design of the measurement equipment is shown in Fig. 1. In the process of the experiments, the heat sink (cold source) is a semiconductor cooling stage (Model J-1); the temperature range of the heat sink is −40 to + 20°C, and the temperature controlling precision for the heat sink is ±0.5°C. The heat source is an electric heating membrane; the temperature range of the heat source is from 20 to 120°C; and the maximum error in the controlled temperature of the heat source is ±0.5°C. The foam glass was in the shape of a cube of $140 \times 140 \times 140\,\mathrm{mm}^3$ during the measurement of thermal conductivity, it was placed between the cold and hot sources, and the polystyrene (its thermal conductivity is $\lambda = 0.02\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$, which is less than that of the specimen) used as thermal insulation material was packaged around the specimen in order to ensure the existence of one-dimensional heat flow in the central region. Four pairs of thermocouples and a heat flow sensor were installed on the upper surfaces of the cube, and another four thermocouples were fixed on the lower surface of the cube. Thermal potentials of the two sets of thermocouples were recorded by means of an Agilent 15970 A data acquisition/switch unit and input to a personal computer, the latter being used to calculate the temperatures on the cold and hot surfaces of the specimen during the measurement. The density of heat flow was determined by a Shotherm HFM heat-flow meter, the measurement range of the heat flow for the heat-flow meter is $100–10000\,\mathrm{J \cdot m^{-2}}$; and the maximum measurement error of the heat flow is ±0.5%. The temperature range of the measurement is −50 to 1000°C; and the maximum error of the temperature measurement is ±0.1°C. In addition, the sensor of the heat-flow meter was fixed on the upper surface of the specimen by means of heat-conduction silicone grease so that a steady heat flow was obtained.

By regulating the temperatures of the heat sink and heat source, the temperature difference ($\Delta\theta$) between them can be maintained in the range of 5–10°C. The values of the heat flow and the equilibrium temperatures were automatically collected at intervals of 5 min by a data acquisition system programmed by a computer. When the relative deviations of five temperature readings were within ±1% of the pre-set temperature value, the equilibrium temperature was assumed to have been reached and the result was recorded.

The reliability of the flat steady-state heat-flow meter has been verified by measuring the thermal conductivity of the Standard Reference Material 1453—expanded polystyrene board. The relative deviation of the experimental thermal conductivities of the material from those given by NIST was observed to be within ±0.5%.

3. RESULTS AND DISCUSSION

3.1. Specific Heat Capacity

123 experimental specific heat-capacity points were collected at temperatures from 79 to 395 K. All experimental results, listed in Table II and plotted in Fig. 2, showed that the structure of the material was stable over the same temperature range; no phase change or thermal decomposition occurred. All experimental points from 79 to 395 K were fitted with a polynomial function of reduced temperature (x) [7] by means of the least-squares method:

$$C_p/\mathrm{J \cdot g^{-1} \cdot K^{-1}} = 0.6889 + 0.3332x - 0.0578x^2 + 0.0987x^3 + 0.0521x^4 - 0.0330x^5 - 0.0629x^6$$

where $x = (T/\mathrm{K} - 237)/158$; 237 was obtained from half the sum of the upper limit temperature (395 K) and the lower limit temperature (79 K), and 158 was from half the difference of the upper limit temperature (395 K) and the lower limit temperature (79 K) in the temperature range of 79 to 395 K; thus, x ranges between +1 and −1. The relative deviations of experimental specific heat capacities from the smoothed heat capacities calculated by the polynomial function were within ±0.35% except for some points around the lower and upper temperature limits.

Table II. Experimental Specific Heat Capacities of Foam Glass 150 P

T(K)	C_p(J · g^{-1} · K^{-1})	T(K)	C_p(J · g^{-1} · K^{-1})	T(K)	C_p(J · g^{-1} · K^{-1})
79.174	0.2155	176.584	0.5483	299.474	0.8139
80.588	0.2264	180.105	0.5572	302.087	0.8212
82.069	0.2389	183.585	0.5664	304.698	0.8302
83.499	0.2460	187.026	0.5755	307.321	0.8373
84.897	0.2512	190.431	0.5837	309.697	0.8437
86.267	0.2569	193.801	0.5917	312.156	0.8491
87.612	0.2639	197.138	0.5998	314.696	0.8579
88.935	0.2703	200.446	0.6064	317.237	0.8633
90.235	0.2731	203.732	0.6143	319.758	0.8687
91.521	0.2779	206.987	0.6221	322.072	0.8771
92.789	0.2837	210.214	0.6311	324.612	0.8799
94.034	0.2913	213.408	0.6374	327.071	0.8842
95.258	0.2919	216.579	0.6444	329.611	0.8892
96.471	0.2992	219.723	0.6518	332.151	0.8949
97.667	0.3025	222.839	0.6607	334.692	0.8999
99.538	0.3059	225.927	0.6693	337.232	0.9069
102.119	0.3178	228.978	0.6749	339.773	0.9131
104.559	0.3307	231.927	0.6849	342.395	0.9237
106.987	0.3389	234.985	0.6934	344.936	0.9237
109.364	0.3473	237.992	0.6966	347.558	0.9308
111.698	0.3563	240.942	0.7051	349.934	0.9333
113.994	0.3650	243.811	0.7119	352.557	0.9422
116.252	0.3721	246.761	0.7169	355.179	0.9482
118.475	0.3788	249.711	0.7236	358.047	0.9514
120.664	0.3863	252.597	0.7246	361.817	0.9585
122.823	0.3946	255.488	0.7284	364.685	0.9653
124.954	0.4015	258.363	0.7353	367.308	0.9699
127.056	0.4084	261.222	0.7399	369.766	0.9727
129.133	0.4152	264.065	0.7424	372.143	0.9769
131.184	0.4219	266.891	0.7489	374.519	0.9784
134.308	0.4253	269.704	0.7537	376.814	0.9877
138.511	0.4418	272.501	0.7577	379.108	0.9929
142.617	0.4541	275.282	0.7631	381.403	0.9987
146.641	0.4669	278.049	0.7689	383.779	1.0015
150.594	0.4781	280.801	0.7736	386.238	1.0083
154.476	0.4887	283.534	0.7820	388.696	1.0107
158.296	0.5003	286.259	0.7858	390.417	1.0154
162.056	0.5122	288.964	0.7915	391.483	1.0157
165.762	0.5214	291.583	0.7969	392.548	1.0196
169.414	0.5311	294.201	0.8001	393.695	1.0221
173.021	0.5401	296.831	0.8064	394.782	1.0272

3.2. Thermodynamic Functions

The smoothed specific heat capacities and thermodynamic functions of foam glass were calculated based on the fitted polynomial equation of

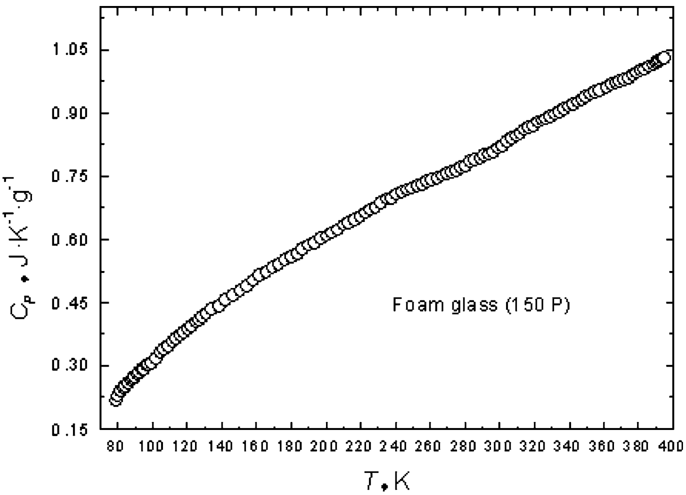

Fig. 2. Plot of specific heat capacities of foam glass 150P versus temperature.

the specific heat capacities as a function of the reduced temperature (x) according to the following thermodynamic relations:

$$H_T - H_{298.15} = \int_{298.15}^{T} C_p dT$$

$$S_T - S_{298.15} = \int_{298.15}^{T} C_p T^{-1} dT$$

The polynomial fitted values of the specific heat capacities and fundamental thermodynamic functions of the sample relative to the standard reference temperature 298.15 K were tabulated in Table III at intervals of 5 K.

3.3. Thermal Conductivity of Foam Glass

The measured thermal conductivities of foam glass from 243 to 395 K are listed in Table IV and plotted in Fig. 3. The measured thermal conductivities of foam glass increase monotonically with temperature from 243 to 395 K, and the values of the thermal conductivities in the same temperature range vary between 0.03 and $0.05\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. The thermal conductivities were low, which showed that the material had excellent performance for thermal insulation and heat preservation. The measured thermal conductivities (λ) versus temperature (T in K) of foam glass were fitted with a polynomial by means of the least- squares method:

Table III. Thermodynamic Functions of Foam Glass 150 P

T(K)	C_p(J · g^{-1} · K^{-1})	$H_T - H_{298.15K}$(J·g^{-1})	$S_T - S_{298.15K}$(J·g^{-1} · K^{-1})
80	0.2346	−123.08	−0.6597
85	0.2568	−121.85	−0.6446
90	0.2780	−120.50	−0.6293
95	0.2982	−119.05	−0.6138
100	0.3175	−117.51	−0.5982
105	0.3361	−115.87	−0.5825
110	0.3539	−114.14	−0.5666
115	0.3712	−112.32	−0.5506
120	0.3880	−110.42	−0.5346
125	0.4043	−108.44	−0.5185
130	0.4201	−106.38	−0.5025
135	0.4354	−104.23	−0.4864
140	0.4505	−102.02	−0.4703
145	0.4652	−99.727	−0.4542
150	0.4795	−97.364	−0.4381
155	0.4936	−94.931	−0.4221
160	0.5074	−92.427	−0.4062
165	0.5209	−89.856	−0.3903
170	0.5341	−87.218	−0.3745
175	0.5471	−84.514	−0.3588
180	0.5598	−81.747	−0.3431
185	0.5723	−78.916	−0.3275
190	0.5846	−76.023	−0.3121
195	0.5966	−73.069	−0.2967
200	0.6084	−70.057	−0.2814
205	0.6201	−66.985	−0.2662
210	0.6315	−63.857	−0.2512
215	0.6427	−60.671	−0.2362
220	0.6537	−57.430	−0.2213
225	0.6646	−54.134	−0.2065
230	0.6753	−50.785	−0.1918
235	0.6858	−47.382	−0.1773
240	0.6962	−43.927	−0.1628
245	0.7066	−40.419	−0.1484
250	0.7168	−36.861	−0.1341
255	0.7269	−33.252	−0.1198
260	0.7371	−29.592	−0.1057
265	0.7471	−25.881	−0.0916
270	0.7572	−22.120	−0.0776
275	0.7673	−18.309	−0.0637
280	0.7774	−14.447	−0.0498
285	0.7876	−10.534	−0.0360
290	0.7978	−6.5709	−0.0223
295	0.8081	−2.5559	−0.0086
298.15	0.8146	0.00	0.00

Table III. (*Continued.*)

T(K)	$C_p(J \cdot g^{-1} \cdot K^{-1})$	$H_T - H_{298.15K}(J \cdot g^{-1})$	$S_T - S_{298.15K}(J \cdot g^{-1} \cdot K^{-1})$
300	0.8185	1.5108	0.0051
305	0.8289	5.6299	0.0186
310	0.8396	9.8019	0.0322
315	0.8503	14.027	0.0457
320	0.8612	18.307	0.0592
325	0.8721	22.641	0.0726
330	0.8832	27.031	0.0859
335	0.8943	31.476	0.0994
340	0.9055	35.977	0.1127
345	0.9166	40.534	0.1260
350	0.9277	45.147	0.1393
355	0.9387	49.815	0.1525
360	0.9494	54.538	0.1657
365	0.9599	59.315	0.1789
370	0.9701	64.144	0.1920
375	0.9796	69.023	0.2051
380	0.9886	73.949	0.2182
385	0.9968	78.919	0.2312
390	1.0139	83.928	0.2441
395	1.0232	88.972	0.2569

Table IV. Experimental Thermal Conductivities of Foam Glass 150 P

T(K)	$\lambda(W \cdot m^{-1} \cdot K^{-1})$	T(K)	$\lambda(W \cdot m^{-1} \cdot K^{-1})$
243	0.0324	321	0.0503
253	0.0359	330	0.0513
262	0.0389	340	0.0525
270	0.0405	351	0.0540
281	0.0423	363	0.0552
291	0.0441	373	0.0565
302	0.0464	382	0.0570
310	0.0487	394	0.0581

$$\lambda/W \cdot m^{-1} \cdot K^{-1} = 0.14433 + 0.00129(T/K) - 2.843 \times 10^{-6}(T/K)^2 + 2.18 \times 10^{-9}(T/K)^3$$

The relative deviations of the fitted thermal conductivities from the experimental values were within ± 0.5%.

3.4. Thermal Diffusivities

The thermal diffusivities (a) were calculated according to the formula:

$$a = \lambda/(\rho C_p)$$

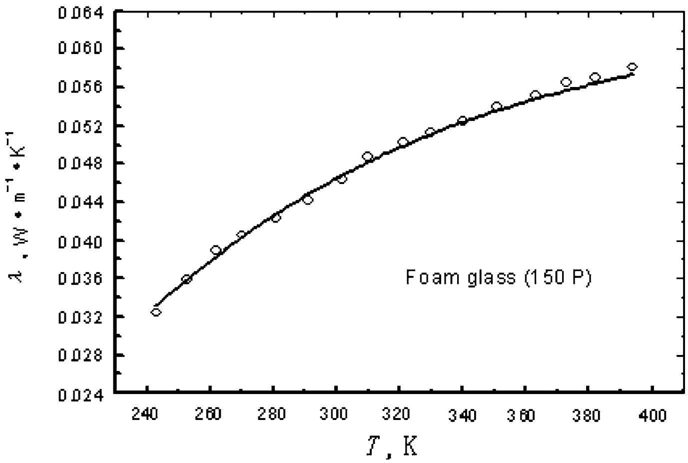

Fig. 3. Plot of thermal conductivities of foam glass 150P versus temperature.

Table V. Thermal Diffusivity of Foam Glass 150 P

T(K)	C_p($J \cdot g^{-1} \cdot K^{-1}$)	λ($W \cdot m^{-1} \cdot K^{-1}$)	a($m^2 \cdot s^{-1}$)
250	0.7168	0.0349	0.3429
260	0.7371	0.0382	0.3638
270	0.7572	0.0405	0.3756
280	0.7774	0.0421	0.3814
290	0.7978	0.0439	0.3905
300	0.8185	0.0460	0.3975
310	0.8396	0.0487	0.4046
320	0.8612	0.0502	0.4087
330	0.8832	0.0513	0.4105
340	0.9055	0.0525	0.4112
350	0.9277	0.0539	0.4109
360	0.9494	0.0549	0.4107
370	0.9701	0.0561	0.4078
380	0.9886	0.0569	0.4053
390	1.0139	0.0577	0.4002

in which λ is the experimental thermal conductivity, ρ is the density of the foam glass (in $g \cdot cm^{-3}$), and C_p is the specific heat capacity of the foam glass. The calculated thermal diffusivities (a) are tabulated in Table V and plotted in Fig. 4. The fitted equation of the derived thermal diffusivities (a) as a function of temperature (T) is given as follows:

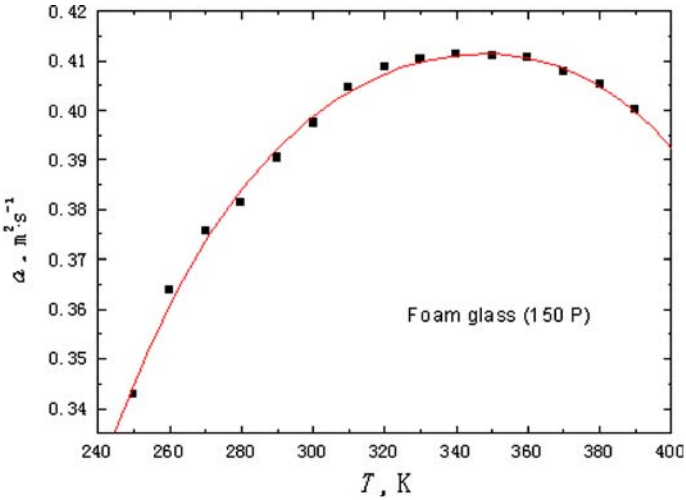

Fig. 4. Plot of thermal diffusivities of foam glass 150P versus temperature.

$$a/\mathrm{m}^2\cdot\mathrm{s}^{-1} = -3.6873 + 0.0447(T/\mathrm{K}) - 1.8820\times10^{-4}(T/\mathrm{K})^2 + 3.6229\times10^{-7}(T/\mathrm{K})^3 - 2.6917\times10^{-10}(T/\mathrm{K})^4$$

The correlation coefficient was $R^2 = 0.99$. The equation is valid at temperatures from 250 to 390 K. The relative deviations of the smoothed values from the calculated values were within ±1%.

3.5. Discussion

The experimental results have shown that 150 P foam glass has low thermal conductivities, and excellent heat-insulation and heat-stability properties. The internal bubbles of foam glass are relative independent and closed, which means the foam glass has advantages of fire prevention, water-proof, resistance to corrosion, and size stability. The foam glass is a kind of heat-preservation material with high strength and low density, which can be used widely in many fields such as water-proof and sound absorption applications.

4. CONCLUSION

(a) Experimental results have shown that both specific heat capacities and thermal conductivities of foam glass 150P increase monotonically with an increase in temperature in the respective experimental temperature ranges of 79–390 K and 250–390 K.

(b) The thermal conductivity of the prepared foam glass was measured to be $0.0324\,W \cdot m^{-1} \cdot K^{-1}$at 233 K, which is less than the maximum value of the thermal conductivity of foam glass 150P at the same temperature, $0.046\,W \cdot m^{-1} \cdot K^{-1}$, given in the literature [8]. The thermal conductivity at 308 K was determined to be $0.0487\,W \cdot m^{-1} \cdot K^{-1}$ in our study, which is less than the maximum value of $0.058\,W \cdot m^{-1} \cdot K^{-1}$ found for the thermal conductivity of foam glass 150P at 308 K given in the literature [8, 9]. Therefore, the prepared foam glass demonstrated that it is characterized by properties which made it an excellent product for use in many applications [8, 9].

(c) A maximum value of the thermal diffusivity of the foam glass 150P was $0.4112\,m^2 \cdot s^{-1}$ at 340 K.

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