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Temperature dependence of thermal transport properties of some synthetic porous insulators

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Abstract. The thermal transport properties of synthetic porous insulators have been measured as a function of temperature. Three samples—foam, closed-cell foam, and fibreglass—have been subjected to different temperatures at different pressures, with compressibility of the samples and the requirements of the technique (transient plane source) taken into account. These materials are used for insulation in temperature control of air-conditioned space and electric appliances, so they are useful in reducing energy losses. The three samples have thermal conductivity, λ, in the range 0.024 – 0.087 W m^{-1} K^{-1}; heat capacity per unit volume, ρC_p, in the range 0.04 – 0.14 MJ m^{-3} K^{-1}; and thermal diffusivity, κ, in the range 0.512×10^{-6} – 0.689×10^{-6} m^2 s^{-1}, with an experimental error not more than 2%. Foam and fibreglass work successfully as good heat insulators in extreme conditions of pressure and temperature (maximum 414 K for the foam, 373 K for the closed-cell foam, and 400 K for the fibreglass). Under different conditions of temperature and pressure, foam as compared to closed-cell foam and fibreglass exhibits insignificant changes in thermal transport properties. Hence foam is the best choice, of the three samples used in the experiment, for thermal insulation under extreme conditions of temperature and pressure.

1 Introduction

In recent years a great amount of attention has been paid to the study of temperature dependence of thermal transport properties—thermal conductivity, λ, heat capacity per unit volume, ρC_p, and thermal diffusivity, κ—of insulators used in different appliances. This is perhaps one of the consequences of the discussion going on all over the world about the amount of exploitable energy reserves. Thermal insulators constitute one of the major areas of porous-ceramic consumption. Insulation power of these materials can be measured in different ways. Measurements of thermal transport properties are important tools in this field. Since temperature variations during heating cycles together with temperature gradients can be determined, operating temperatures and thermal stresses can be easily assessed.

The technique used by us was the transient plane source (TPS) (Gustafsson et al 1979; Gustafsson 1991). This technique has high potential for the measurement of thermal transport properties of a variety of solids. Many insulators have been studied by this technique, for example ceramic fibre over a range of temperatures and pressures (Maqsood et al 2000), and rocks over a range of temperatures (Shabbir et al 1993, 2000). High-T_c superconductors (Maqsood et al 1996) have also been studied by this technique. It covers a wide range of thermal conductivity (0.02 – 200 W m^{-1} K^{-1}) (Suleiman et al 1993) and temperature (77 – 1073 K) (Maqsood et al 2000).

We studied thermal transport properties of three synthetic porous insulators: foam, closed-cell foam, and fibreglass, under different conditions. The samples were obtained from Sabro International Air Conditioners, Islamabad, Pakistan. The manufacturer of the closed-cell foam is Insulflex SDN, BHD, Malaysia. Closed-cell foam provides an ideal and most efficient vapour barrier for the prevention of condensation or frost formation in cooling systems, chilled water, and refrigerator lines. The manufacturer of the fibreglass is Owens-Corning Fibreglass Corp. Normally specified for a wide variety of insulation requirements, both unfaced and Kraft-faced fibreglass blanket insulations are designed to be used between metal or wood studs in the exterior walls of commercial buildings. These products may also be used over suspended-ceiling systems for improved thermal/acoustical performance, provided the ceiling board and the grid system can support the additional weight, and the ceiling assembly is not fire-resistance rated.

In the light of this research one can select the material with optimum performance, appropriately low thermal expansion and conductivity, for use at high temperatures and/or pressures, providing insulation with a high margin of safety and space at lowest cost. As a result, proper type of insulation can be recommended in accordance with the specific application.

2 Experimental procedure

2.1 *Sample preparation*

The foam, closed-cell foam, and fibreglass samples were prepared in such a way that their thickness was not less than the minimum required probing depth (Gustafsson et al 1979, 1984). A special sample holder (Maqsood et al 2000) was used so that the applied pressure was transmitted to the sample symmetrically downwards. Sample specifications and dimensions are given in table 1. Sample descriptions are given below.

Table 1. Sample specification at room temperature and atmospheric pressure (101.33 kPa).

Sample	Length/cm [a]	Width/cm [a]	Thickness/cm [a]	Volume/cm^3	Mass/g [b]	Density/kg m^{-3}	Pores/mm^2
Foam	4.971	6.550	2.563	83.45 ± 0.30	2.002	23.99 ± 3.23	5
Closed-cell foam	5.215	3.589	0.957	17.91 ± 0.13	3.700	206.77 ± 7.35	2
Fibreglass	6.050	4.300	2.520	65.55 ± 0.25	4.550	69.29 ± 3.86	

[a] ± 0.005 cm; [b] ± 0.001 g.

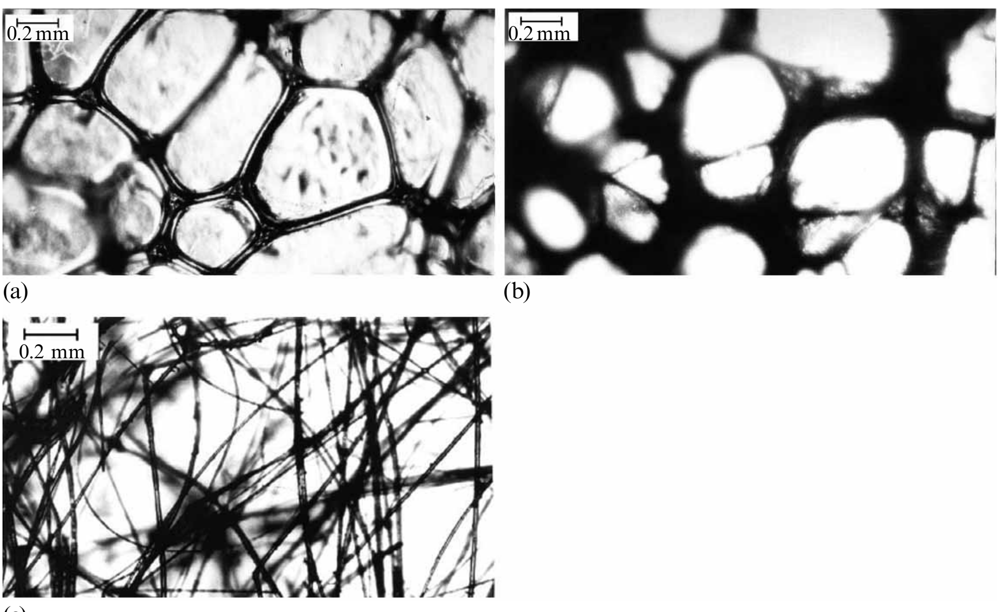

Figure 1. Microscopic views of (a) foam, (b) closed-cell foam, and (c) fibreglass.

2.1.1 *Foam.* The colour of the foam was light yellow; the foam was light in weight, flexible, and locally manufactured. From a microscopic examination (figure 1a), it has been found that the cells were closed and filled with air. The cells differed in size and were of irregular shape. Some cells were spherical, most of them were hexagonal. They were randomly distributed in the material. The average diameter of the smallest cell was 0.25 mm and that of the largest about 0.7 mm. In a cross-sectional area of 38.5 mm^2, the number of cells was 200.

2.1.2 *Closed-cell foam.* Closed-cell foam is a flexible and elastomeric nitrile rubber material, designed for thermal insulation. It is black in colour, available in tubing and sheet form. The extruded flexible tubing is specially designed to fit the standard diameter of steel and copper piping. Sheets are available in standard pre-cut sizes or in rolls. A microscopic examination (figure 1b), has shown that some cells were spherical and a few were deformed spheres. The cells were distributed in the solid material of closed-cell foam and were not interconnected with each other. Most of the material was solid. The average diameter of the smallest cell was 0.25 mm and that of the largest cell was 0.85 mm. The number of cells in a cross-sectional area of 38.5 mm^2 was about 80.

2.1.3 *Fibreglass.* The sample was yellow in colour, flexible, and formed from uniformly textured glass wool fibres bonded with thermosetting resin. The base materials are sand, soda ash, and limestone. The commercial name of the sample is 'ductwrap'. Unfaced insulation has a low flame-spread rating. A microscopic view of the sample is shown in figure 1c.

2.2 *Measuring procedure*

The measurements were carried out with the apparatus, the circuit diagram of which was shown earlier (Maqsood et al 2000). A TPS element with bifilar nickel wire 10 μm thick and a disk with a diameter 20 mm was used. The resistance of the element and its thermal coefficient of resistivity, at room temperature (25 °C), were 5 Ω and 4.961×10^{-3} K^{-1}, respectively. The resistivity coefficients of the TPS at different temperatures and pressures were determined experimentally according to the procedure described by Maqsood et al (1996, 2000) and the TPS element was sandwiched between the two pieces of the sample and then placed in an electric oven. A constant current of 50.0 mA was fed to the element for 165 s. The optimum time window (Bohac et al 2000) for determining thermal conductivity, heat capacity per unit volume, and thermal diffusivity from a single transient recording has been identified as the interval $0.18 < t_{max}/\theta < 0.82$. For the $V-t$ (voltage – time) plot, 100 data points were recorded in 165 s. Thermal conductivity, heat capacity per unit volume, and thermal diffusivity, with the corresponding values of probing depth, temperature increment, time correction, and θ were calculated with the use of a computer program. The data were collected at different temperatures by placing the element with the sample in an electric oven. The temperature was measured with a mercury thermometer as well as the oven thermocouple, to within 2 K. At each temperature, pressure was applied, by placing loads on the sample, one by one. At high pressures small deformations are produced in the sample in the direction of applied pressure. For this reason, many samples with the same dimensions were made and used. All the measurements were made in air. In our records the atmospheric pressure (101.33 kPa) was added to the calculated applied pressure. The range of the temperatures and pressures for each sample varied depending upon their nature. For the foam it was 300 – 415 K and 101 – 109 kPa, for closed-cell foam it was 300 – 375 K and 101 – 116 kPa, and for the fibreglass it was 300 – 400 K and 101 – 117 kPa, respectively.

2.3 *Calibration of the apparatus*

The calibration of the apparatus was done with a sample of quartz standard. Quartz was used because its properties are well known, and because, like our samples, it is an insulator. The sample consisted of two identical optically polished disks, 30 mm in diameter and 10 mm thick, with an apparent density of 2372 kg m^{-3}. The measured thermal conductivity, heat capacity per unit volume, and thermal diffusivity of quartz standard are listed in table 2, together with the reference data reported by Gustafsson et al (1979), and it is seen that the agreement is good. The experimental error is within 2%, which confirms that our experimental setup can be used for the measurements of thermal transport properties (Maqsood et al 1996).

Table 2. Results of measurements of thermal transport properties of fused quartz at room temperature. The published data (Gustafsson et al 1979) are also provided for the comparison. Mean values with standard deviations shown in parentheses.

Parameters	Published data	Our data	Experimental error/%
λ/W m^{-1} K^{-1}	1.420 (0.002)	1.390 (0.004)	2.10
ρC_p/MJ m^{-3} K^{-1}	1.650 (0.004)	1.620 (0.003)	1.81
$\kappa/10^{-6}$ m^2 s^{-1}	0.863 (0.002)	0.851 (0.007)	1.40

3 Results and discussion

High-temperature data were collected for different pressures. The temperature range was different for each sample. For the foam it was 300 – 414 K. Measurements were carried out at these temperatures at four different pressures, one at a time. The temperature range for the closed-cell foam was 300 – 373 K. Again, measurements were carried out at these temperatures at four different pressures, one at a time. The temperature range for the fibreglass was 300 – 398 K. Five different pressures, one at a time, were used at these temperatures. The data obtained for the three materials listed in tables 3, 4, and 5 and discussed in detail below.

3.1 *Foam*

The data for the thermal transport properties of foam as a function of temperature at different pressures are listed in table 3. The behaviour of λ with temperature is plotted in figure 2. It is seen that λ first increases slightly and then decreases with the increase of temperature. The increase in λ with temperature is usual for solid insulators, and is due to the increase in the number of excited phonons. We can also consider λ in terms of the different heat transfer mechanisms (Patten and Shochdopole 1962)

$$\lambda = \lambda_g + \lambda_s + \lambda_c + \lambda_r \ , \tag{1}$$

where λ_g is the thermal conductivity due to gas (air); λ_s is the thermal conductivity due to the solid material; λ_c is the contribution due to convection; and λ_r is the contribution due to radiation.

Here λ_g of the component gases in air increases with the increase of temperature. This causes a rise in λ with temperature. As the temperature is further increased the thermal activity and lattice vibrations increase, which lead to a short mean path, and when scattering increases λ decreases. This type of behaviour is also observed in low-temperature studies of insulators and the following expression is often used to account for this behaviour (Sepulvede et al 1999):

$$\lambda = (A + BT)^{-1} \ , \tag{2}$$

Table 3. Thermal transport properties of foam as a function of temperature at constant pressures. Standard deviations of the mean of four readings are shown in parentheses, indicating the error in the last decimal place.

Pressure/kPa	Temperature/K	λ/W m^{-1} K^{-1}	ρC_p/MJ m^{-3} K^{-1}	κ/10^{-6} m^2 s^{-1}
101.33	300(1)	0.035(8)	0.059(1)	0.605(3)
	323(1)	0.038(4)	0.064(7)	0.603(4)
	345(1)	0.033(2)	0.058(2)	0.604(2)
	374(1)	0.028(1)	0.047(2)	0.603(5)
	414(1)	0.027(3)	0.044(6)	0.607(2)
102.99	300(1)	0.037(1)	0.061(1)	0.560(9)
	323(1)	0.050(5)	0.055(6)	0.573(5)
	345(1)	0.044(2)	0.060(2)	0.561(3)
	374(1)	0.040(5)	0.062(1)	0.603(3)
	414(1)	0.034(2)	0.058(4)	0.598(1)
104.66	300(1)	0.043(7)	0.071(3)	0.601(1)
	323(1)	0.045(3)	0.074(6)	0.604(2)
	345(1)	0.038(2)	0.066(2)	0.603(3)
	374(1)	0.030(3)	0.053(7)	0.577(4)
	414(1)	0.040(5)	0.067(9)	0.605(1)
108.65	300(1)	0.050(5)	0.085(1)	0.605(2)
	323(1)	0.055(9)	0.092(8)	0.603(4)
	345(1)	0.052(3)	0.081(2)	0.604(2)
	374(1)	0.051(2)	0.085(4)	0.605(1)
	414(1)	0.034(1)	0.074(3)	0.596(7)

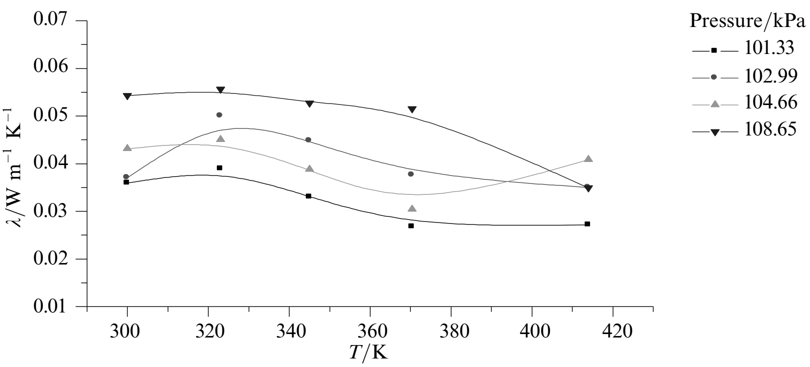

Figure 2. Variation of thermal conductivity of the foam with temperature at different pressures. The errors are given in table 3.

where A and B are material-dependent constants: A is related to the collective contribution of scattering by all point defects or structural deformations in pores, and B is associated with intrinsic thermal conductivity due to phonon–phonon interactions (Umklapp process). ρC_p behaves in the same way, whilst κ undergoes only a small change with temperature. The variations of λ, κ, and ρC_p follow the relation

$$\lambda = \kappa \rho C_p \ . \tag{3}$$

Unusual behaviour (a small increase) in thermal parameters is observed at higher pressures and temperatures (104.66 kPa, 414 K). The rise in λ may be due to the rise in λ_r in equation (1). Equation (2) can be modified as follows (Sepulvede et al 1999),

$$\lambda = (A + BT)^{-1} + CT^3 \tag{4}$$

where $C = A'\sigma$. Here $A' = 0.0320$ for heat flux perpendicular to the axis of the pores (figure 3a) and $A' = 0.0435$ for heat flux parallel to the axis of the pores (figure 3b) (Rudiger et al 1976); σ is the Stefan Boltzmann constant whose value is 5.67×10^{-12} W cm^{-2} K^{-4}. ρC_p and κ behave in the same way but the incremental changes for κ are very small. The curves in figure 4 indicate that at high pressures λ and ρC_p have relatively high values, owing to the escape of gases from the pores.

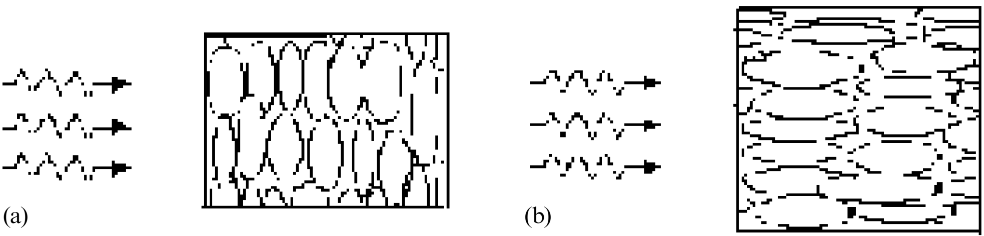

Figure 3. Orientation of pores with respect to thermal radiation: (a) heat flux perpendicular to the axis of the pores, (b) heat flux parallel to the axis of the pores.

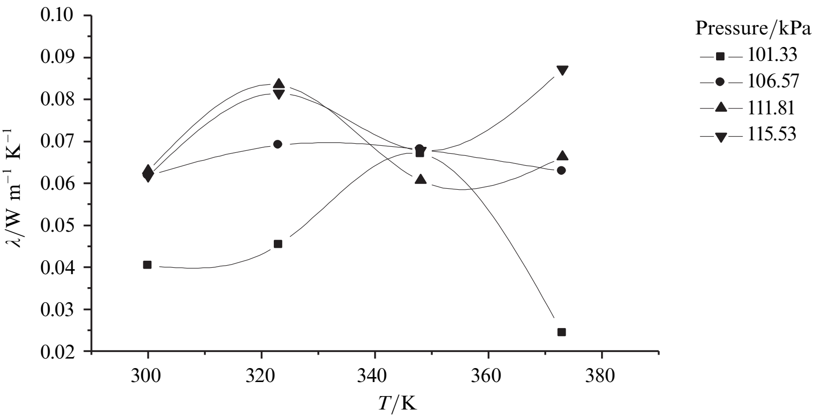

Figure 4. Variation of thermal conductivity of the closed-cell foam with temperature at different pressures. The errors are given in table 4.

3.2 *Closed-cell foam*

The data for the thermal transport properties as a function of temperature at different pressures are collected in table 4. The variation of λ with temperature is shown in figure 4. It is seen that in the case of closed-cell foam there are two types of curves, each describing a different behaviour: a pair of curves at 101.33 kPa and 106.57 kPa, and another one at higher pressures (111.81 kPa and 115.53 kPa). The first pair follows equations (1) and (2), and the second pair follows equation (4). It is also seen from figure 4 and table 4 that at the highest temperature of 373 K the values of λ and ρc_p increase with increasing pressure. The other feature which is observed is a similar behaviour of different curves at 348 K. Here λ and ρC_p are almost independent of pressure. This temperature (348 K) is the glass transition temperature, T_g, for closed-cell foam (Sandberg and Bäckström 1979). Below this temperature the material behaves as rubber and above it, it behaves as glass. The region under the curve below T_g is called the rubber region, and above T_g the glass region. In the rubber region the number of excited phonons increases with the increase of temperature. This causes an increase in λ and ρC_p.

Table 4. Thermal transport properties of closed-cell foam as a function of temperature at constant pressures. Standard deviations of the mean of four readings are shown in parentheses, indicating the error in the last decimal place.

Pressure/kPa	Temperature/K	λ/W m^{-1} K^{-1}	ρC_p/MJ m^{-3} K^{-1}	κ/10^{-6} m^2 s^{-1}
101.33	300(1)	0.040(2)	0.076(6)	0.531(7)
	323(1)	0.045(5)	0.060(3)	0.586(3)
	348(1)	0.062(1)	0.112(2)	0.595(7)
	373(1)	0.024(2)	0.047(3)	0.512(8)
106.57	300(1)	0.061(5)	0.119(2)	0.528(9)
	323(1)	0.069(1)	0.112(1)	0.601(5)
	348(1)	0.068(1)	0.113(2)	0.598(3)
	373(1)	0.062(2)	0.105(3)	0.593(4)
111.81	300(1)	0.062(2)	0.128(2)	0.550(1)
	323(1)	0.083(6)	0.141(9)	0.591(1)
	348(1)	0.060(1)	0.107(2)	0.530(1)
	373(1)	0.066(3)	0.123(6)	0.539(5)
115.53	300(1)	0.061(7)	0.109(1)	0.561(1)
	323(1)	0.081(4)	0.136(8)	0.595(1)
	348(1)	0.067(4)	0.112(1)	0.602(1)
	373(1)	0.087(4)	0.114(6)	0.598(4)

3.3 *Fibreglass*

The data for the thermal transport properties as a function of temperature at different pressures are collected in table 5. The variation of λ with temperature as shown in figure 5, is small. In this case data have been obtained at five different pressures. It is seen that λ and ρC_p undergo small, smooth, and consistent changes with temperature. At each pressure, an initial rise in temperature causes a small increase and after that a decrease in the values take place. This type of behaviour of parameters can be best explained by equations (1) and (2). The data point at 108.86 kPa and 373 K is seen to have a small deviation from the above behaviour of other curves. This may be due to an experimental error. At room temperature, λ and ρC_p have the lowest values; here an increase in pressure has a negligible effect on the values of the measured parameters. This is due to the glass nature of the sample as a result of which increasing pressure causes smaller compression in the sample.

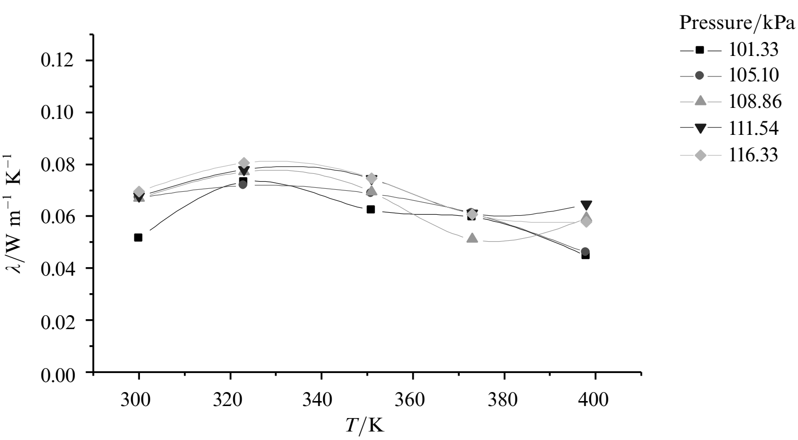

Figure 5. Variation of thermal conductivity of the fibreglass with temperature at different pressures. The errors are given in table 5.

Table 5. Thermal transport properties of the fibreglass as a function of temperature at constant pressures. Standard deviations of the mean of four readings are shown in parentheses, indicating the error in the last decimal place.

Pressure/kPa	Temperature/K	λ/W m^{-1} K^{-1}	ρC_p/MJ m^{-3} K^{-1}	$\kappa/10^{-6}$ m^2 s^{-1}
101.33	300(1)	0.051(2)	0.087(4)	0.590(1)
	323(1)	0.080(1)	0.123(1)	0.587(5)
	348(1)	0.058(1)	0.097(1)	0.594(9)
	373(1)	0.061(1)	0.107(1)	0.557(3)
	398(1)	0.044(8)	0.078(1)	0.570(2)
105.10	300(1)	0.066(5)	0.109(8)	0.593(7)
	323(1)	0.071(8)	0.123(6)	0.578(4)
	348(1)	0.068(5)	0.118(8)	0.582(3)
	373(1)	0.061(1)	0.101(2)	0.603(2)
	398(1)	0.046(8)	0.067(1)	0.689(1)
108.86	300(1)	0.066(1)	0.111(2)	0.598(5)
	323(1)	0.077(4)	0.113(2)	0.587(3)
	348(1)	0.069(9)	0.116(1)	0.596(2)
	373(1)	0.051(8)	0.061(1)	0.556(4)
	398(1)	0.059(5)	0.086(8)	0.683(1)
111.54	300(1)	0.067(3)	0.113(4)	0.594(5)
	323(1)	0.077(4)	0.130(6)	0.596(6)
	348(1)	0.074(1)	0.125(3)	0.597(8)
	373(1)	0.061(3)	0.104(4)	0.584(2)
	398(1)	0.064(5)	0.094(9)	0.689(1)
116.33	300(1)	0.069(3)	0.121(1)	0.575(3)
	323(1)	0.080(1)	0.131(2)	0.613(3)
	348(1)	0.074(1)	0.126(2)	0.589(9)
	373(1)	0.060(4)	0.103(4)	0.587(1)
	398(1)	0.057(3)	0.097(5)	0.594(5)

4 Conclusions

The values of λ and ρC_p measured for the three samples are very low (0.024_2–0.087_4 W m^{-1} K^{-1} and 0.04–0.14 MJ m^{-3} K^{-1}, but they are seen to vary with applied temperature and pressure). If we compare the results for the three samples, then it is clear that foam has comparatively low values of λ and ρC_p (0.027–0.055 W m^{-1} K^{-1}; 0.044–0.092 MJ m^{-3} K^{-1}). In the case of λ, the total difference in the temperature and pressure ranges investigated is 0.028 W m^{-1} K^{-1}. λ shows less dependence upon temperature but is greatly affected by the applied pressure. Closed-cell foam has values of λ and ρC_p of 0.02–0.08 W m^{-1} K^{-1} and 0.04–0.14 MJ m^{-3} K^{-1}, respectively. It gives good results where the temperature varies and pressure is high (106–116 kPa). In this range the fluctuation is very small. The third sample, fibreglass, shows similar behaviour to foam, but here the values of thermal parameters are relatively high. There is less variation with temperature and pressure, for example the fluctuation of λ is within 0.036 W m^{-1} K^{-1}. These behaviours of the samples with the temperature lead to the conclusion that foam is a good choice where pressure changes little but the temperature varies. When external stresses are present and temperature varies, fibreglass and closed-cell foam also give good results.

From the above discussion it is clear that foam, closed-cell foam, and fibreglass are all suitable insulators because of the low values of their thermal transport properties and their behaviour under extreme conditions of pressures and temperatures. We can therefore conclude that all these materials are suitable for insulation purposes in scientific and commercial fields.

There is a need for a concluding remark about the best choice of insulation among the three samples. This will help the agency, working with the "Energy Saving" project. The criterion for this choice would be that the insulation should have very small and consistent value of thermal conductivity under extreme environmental conditions of temperature and stresses. From this point of view foam is the best choice because of its lowest values, fibreglass is a good choice because of its consistency with pressure and temperature, and, finally, closed-cell foam is the third choice because of its plastic nature and high density.

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