

THERMAL PROPERTIES OF PHENOLIC FOAM INSULATION

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ABSTRACT

This paper presents experimental results concerning thermal properties of phenolic foams, with or without activated carbon. Effective thermal conductivity (k_{eff}) of various samples is measured using heat flow thermal conductivity testers that comply with ASTM C518. Transmittance spectra are taken using FTIR for samples of various densities. Extinction coefficient spectra are obtained by applying Beer's law. The Rosseland mean extinction coefficients and radiative thermal conductivities are then obtained for various temperatures. Results show that k_{eff} increases with temperature. Furthermore, it takes only approximately 2 hours for the sample to become saturated with moisture. The k_{eff} of saturated samples is about 20 % higher than that of the dry samples. Addition of activated carbon shows no appreciable effect on k_{eff} . The extinction coefficient increases with sample density. Radiation accounts for approximately 15% of the total heat transfer for phenolic foams at near room temperatures.

I. INTRODUCTION

Thermal insulation materials have important applications in aerospace engineering, nuclear engineering, cryogenics, building and industry. The main functions of thermal insulation are the conservation of energy, the control of temperature, and the control of heat transfer (Tien and Wang, 1984). Thermal insulations can be categorized into various types, such as simple vacuum systems, powder insulations, fibrous insulations, foam insulations, and multi-layer insulations. Among these, foam insulations are the most widely used insulations in engineering applications due to their low cost and ease of manufacture and maintenance. Polyurethane (PU) foams are the most popular foam insulation because they have low thermal conductivity and good mechanical strength (Sparks and Arvidson, 1984). Tseng *et al.* (1997)

measured the thermal conductivity of PU foams from room temperature down to liquid hydrogen temperature (20K). Wu *et al.* (1999) measured the thermal conductivity of PU foams at near room temperatures under various pressures. Although PU foams have good insulating properties, they can not be used in acid or alkali environments. Other popular foam insulations include polyethylene (PE), and polystyrene (PS) foams. PE foams are good electrical insulators and do not absorb much moisture. While all PU, PE, and PS foams provide good thermal insulation performance, they are easy to burn, so that they are not suitable for use where fire hazard is an important consideration. Phenolic resins, on the other hand, are not easy to burn. Even when they do burn, they do not drip. With their good flame-retardant properties (Costa *et al.*, 1998), phenolic foams are suitable for use as building insulation and in other industrial

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applications. In this work, we will present measurement results of radiative properties and effective thermal conductivity of phenolic foams.

Phenolic foam is a rigid, thermoset product that is low in cost and dimensionally stable and has excellent flame resistance. It is made from liquid phenol-formaldehyde resin. A foaming agent is added. When hardener is added to the mix and rapidly stirred, the exothermic reaction of the resin, together with the action of the foaming agent, causes foaming of the resin. This is followed by rapid setting of the foamed material (Stevens, 1990). The foam samples used in the present study were obtained from Hsinyin Plastics Co. in Taoyuan, Taiwan. We used 9 samples of different densities. Samples A, B, C, D, and J are pure phenolic foams. Samples E, F, G, and H are doped with 5% wt of fine activated carbon powders. Adding activated carbon can reduce the amount of smoke caused by CFC blowing agents in case of fire. Furthermore, activated carbon is an expansion type fire retarder, so it can increase the fire retardation capability of the insulating foam.

II. HEAT TRANSFER THEORY

The major heat transfer mechanisms responsible for heat flow in thermal insulations are gas conduction, solid conduction, and radiation. Because of the complex interactions of various mechanisms, it is practically useful and convenient to define an "effective" (or "apparent") thermal conductivity, k_{eff} , to characterize the thermal effectiveness of the insulation. For a one-dimensional case, k_{eff} is defined as

$$q = k_{eff}(T_1 - T_2)/L \quad (1)$$

where q is the net heat flux through the insulation, T_1 and T_2 the boundary temperatures, and L the insulation thickness. For optically thick media, the radiative heat flux can be expressed as (Siegel and Howell, 1992):

$$q_r(x) = -\frac{4}{3\sigma_{e,R}} \cdot \frac{\partial e_b}{\partial x} = -\frac{16}{3\sigma_{e,R}} \sigma T^3 \cdot \frac{\partial T}{\partial x} = -k_r \frac{\partial T}{\partial x} \quad (2)$$

where T is the medium temperature, σ_b the blackbody emissive power, σ the Stefan-Boltzmann constant, k_r the radiative thermal conductivity, and $\sigma_{e,R}$ the Rosseland mean extinction coefficient. With diffusion approximation, radiation and conduction are decoupled, and the effective thermal conductivity can be written as

$$k_{eff} = k_r + k_c \quad (3)$$

where k_c is the conduction contribution from gas and solid.

The Rosseland mean extinction coefficient is defined as

$$\begin{aligned} \frac{1}{\sigma_{e,R}} &= \int_0^\infty \frac{1}{\sigma_{e\lambda}} \frac{\partial e_{b\lambda}}{\partial T} d\lambda \bigg/ \int_0^\infty \frac{\partial e_{b\lambda}}{\partial T} d\lambda \\ &= \int_0^\infty \frac{1}{\sigma_{e\lambda}} \frac{\partial e_{b\lambda}}{\partial e_b} d\lambda \end{aligned} \quad (4)$$

where $e_{b\lambda}$ is the spectral blackbody emissive power, and $\sigma_{e\lambda}$ is the spectral extinction coefficient. The Rosseland mean extinction coefficient is an average value of $\sigma_{e\lambda}$ weighted by the local spectral energy flux. If we can measure $\sigma_{e\lambda}$, we can obtain $\sigma_{e,R}$ from the above equation, and then calculate radiative heat flux from Eq. (2). In practice, due to limitations of spectrometers, $\sigma_{e\lambda}$ is obtained only in the near infrared region where most thermal energy radiates.

III. THE PROPERTY MEASUREMENTS

In this work, the effective thermal conductivity is measured by using the Lambda 2000 manufactured by Holometrix, Inc. The Lambda 2000 is based on the heat flow meter method and complied with ASTM C518 (ASTM Standard, 1995). It accepts 300-mm square samples up to 100 mm thick. In this work, samples of 2.2 cm thick are used.

The temperature difference between the hot and the cold plates is set at 10°C. Tests are done at atmospheric pressure. The apparatus is first calibrated using standard reference material SRM 1450C (1997) from NIST before measurements. The uncertainty of the measurement is estimated to be $(\Delta k_{eff}/k_{eff}) = 5.5\%$.

For intermediate temperature (300 K to 500 K) applications, most thermal energy radiates in the near infrared region. Usually, one uses a Fourier transform infrared spectrometer (FTIR) to measure the transmittance spectrum of an insulation sample. The spectral extinction coefficients for thin homogeneous samples can be obtained by using Beer's law:

$$T_{n\lambda} = e^{-\sigma_{e\lambda}L} \quad (5)$$

where $T_{n\lambda}$ is the spectral transmittance and L is the thickness of the sample. The above relation is valid for internal transmittance within the sample. To account for the interface reflections, the total transmittance can be written as

$$T_{n\lambda} = (1 - \rho)^2 e^{-\sigma_{e\lambda}L} \quad (6)$$

where ρ , is the reflectivity at the interface. In Eq. (6), multiple reflections are neglected because the

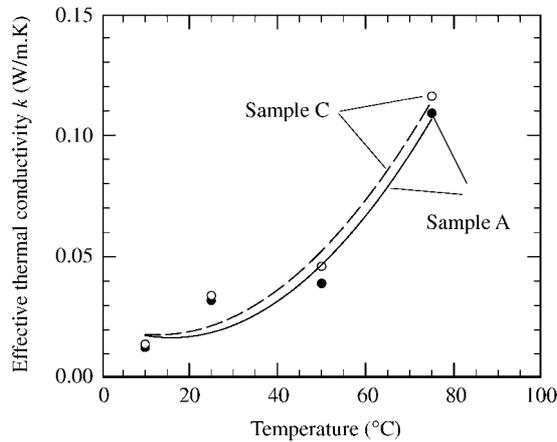


Fig. 1 The effective thermal conductivity of samples A and C at various temperatures. Density of sample A=46.3 kg/m³, density of sample C=66.6 kg/m³

measured transmittance is very low. For phenol formaldehyde resins, the average refractive index, n , is approximately 1.59 (Brandrup *et al.*, 1999). Assuming a constant refractive index, the reflectivity can be estimated as $\rho=(n-1)^2/(n+1)^2=0.052$. The transmittance can finally be obtained from

$$\sigma_{e\lambda} = -\frac{\ln T_{n\lambda} - \ln(1-\rho)^2}{L} \quad (7)$$

For $T_{n\lambda} < 0.1$ and $\rho=0.052$, the correction for the interface reflection accounts for less than 5% of extinction coefficient values. The Rosseland mean extinction coefficient can then be calculated from Eq. (4). The FTIR used in this work is a Perkin-Elmer Spectrum 2000 model. After conductivity measurements, the samples are sectioned and transmittance measurements are performed.

IV. RESULTS AND DISCUSSION

Figure 1 shows the effective thermal conductivity of samples A and C at various temperatures. The effective thermal conductivity increases with temperature, quadratically, in the temperature range. For small temperature differences, solid conduction varies linearly with temperature. Radiation contribution in these foams varies cubically with temperature at near room temperatures (see discussion on Figs. 7a and 7b). Therefore, the quadratic dependence of k_{eff} on temperature shows both conduction and radiation effects. Sample C has slightly higher thermal conductivity than sample A due to its higher density.

The variation of the effective thermal conductivity of phenolic foam with its density is presented

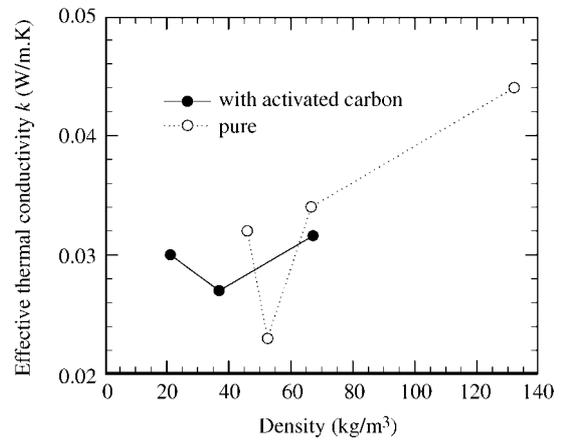


Fig. 2 The effects of density on the effective thermal conductivity of phenolic foams with and without activated carbon, at 25°C. Samples are dried at 50°C for 24 hours before measurements

in Fig. 2 for pure samples and samples with activated carbon. There seems to exist a minimum effective thermal conductivity for each type of sample. The minimum value occurs at the density of 50 kg/m³ for pure samples and 40 kg/m³ for samples with activated carbon. For samples with higher densities, the effective thermal conductivity increases with density due to the increase of heat transfer through solid conduction. For samples with lower densities, as we shall see later, the radiative thermal conductivity increases as the density decreases, and therefore the effective thermal conductivity also increases.

In practical applications, moisture in the air may gradually diffuse into insulation foams, and thus reduce the effectiveness of the insulation. It is of interest to know how fast this will occur especially in wet climate areas such as Taiwan. We first dry sample J at 50°C for 24 hours; air-cool the sample in a dry box for 12 hours; expose the sample in an atmosphere of 80% relative humidity for two hours and measure the effective thermal conductivity at 25°C. Then we expose the same sample again for another two hours; and again measure the effective thermal conductivity at 25°C. This process is repeated for a total of 5 times. The results are plotted in Fig. 3. Surprisingly, it takes only two hours for the conductivity to increase by 20% and it seems to saturate within 10 hours. Therefore, it is a good idea to have some protective film coated on the foam surfaces to prevent moisture from penetrating into the insulation foams.

Figure 4 depicts the transmittance spectra for sample B. The transmittance decreases as the sample thickness increases. The absorption bands of water at 2.7 μm and 6.3 μm can be seen in the spectra. Although the samples were dried at 50°C for 24 hours before the transmittance measurements, the drying

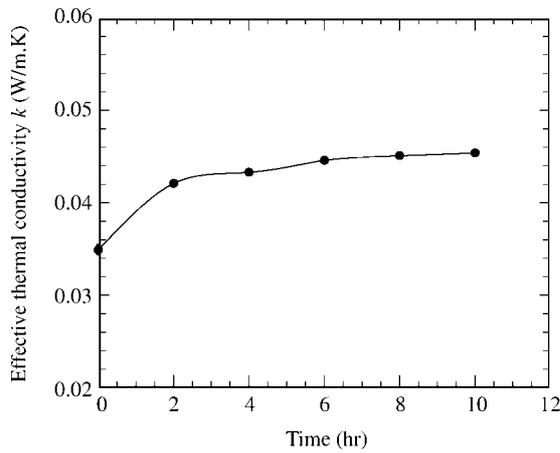


Fig. 3 Variation of the effective thermal conductivity with time at 25°C

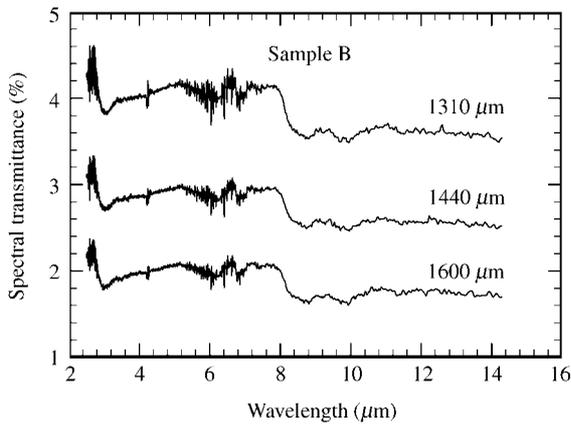
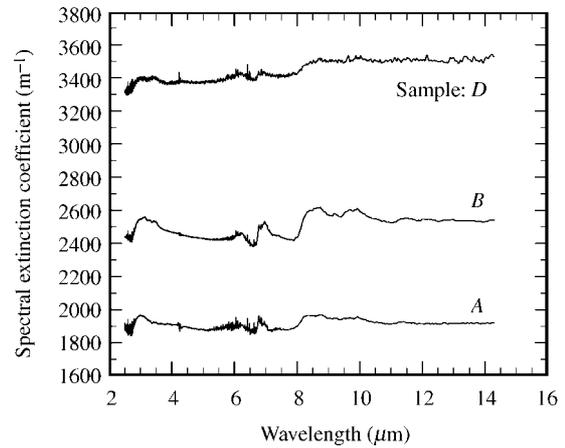


Fig. 4 Transmittance spectra for sample B. The sample thickness is indicated

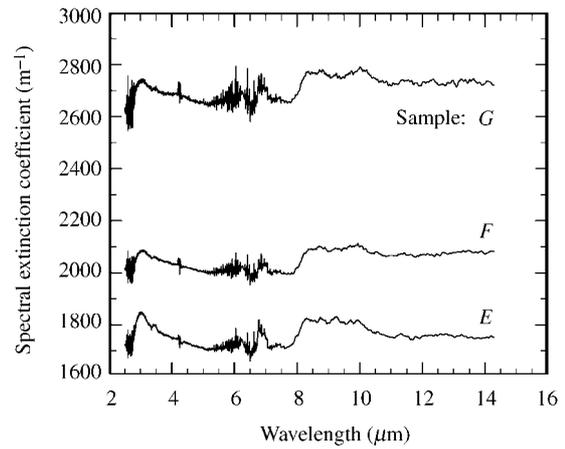
process can only removed free-molecule water. Water that exists as bonded molecules would remain in the sample, and this accounts for the 2.7 μm and 6.3 μm absorption bands. Phenolic foams have lower transmittance for wavelengths longer than 8 μm .

The extinction coefficient spectra for samples with and without activated carbon are presented in Fig. 5. They are obtained by using Eq. (7) and the transmittance data. The extinction coefficient is slightly higher in the longer wavelength region so that phenolic foams would block more thermal radiation from lower temperature than from higher temperature. The spectra have similar trends because the base materials are the same. Note that sample *F* (36.9 kg/m^3) has lower density than sample *A* (46.3 kg/m^3), yet its extinction coefficient is higher than sample *A*'s. So adding activated carbon seems to increase the extinction coefficient slightly.

Figure 6 shows the variation of the Rosseland mean extinction coefficient $\sigma_{e,R}$ with temperature for samples without activated carbon. Since $\sigma_{e,R}$ is an



(a)



(b)

Fig. 5 Extinction coefficient spectra for samples with (E, F, G) and without (A, B, D) activated carbons

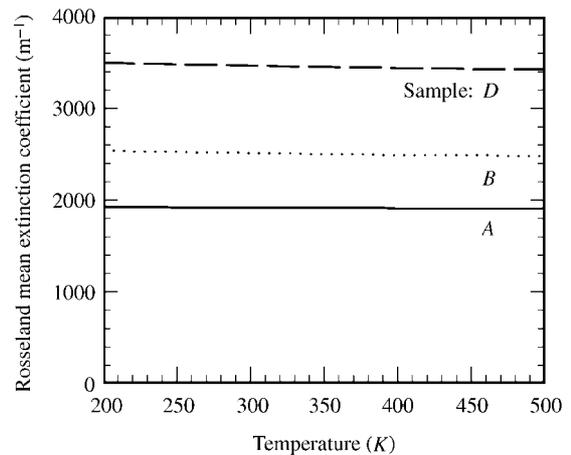


Fig. 6 Rosseland mean extinction coefficients of pure phenolic foam

average extinction coefficient over the spectrum weighted by the emissive power, it represents the ability to extinguish thermal radiation at certain

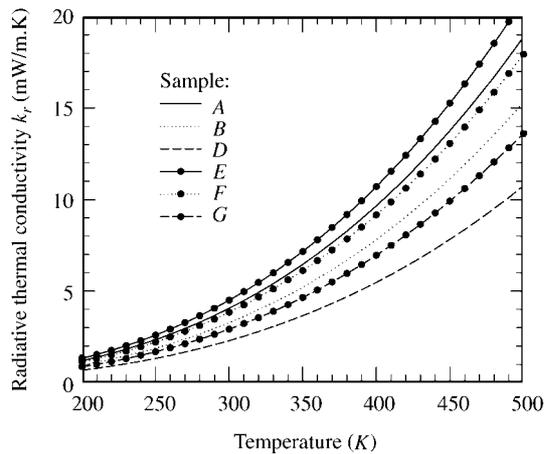


Fig. 7 Radiative thermal conductivity at various temperatures for samples with (E, F, G) and without (A, B, D) activated carbons

temperatures. The results show $\sigma_{e,R}$ decreases only slightly as temperature increases. According to Wein's displacement law, when temperature decreases from 500 K to 200 K, the corresponding wavelength at which the spectral emissive power is maximum shifts from $5.8 \mu\text{m}$ gradually to $14.5 \mu\text{m}$. Because the spectral extinction coefficient only increases slightly, so does the Rosseland mean extinction coefficient. Increasing the insulation density also increases $\sigma_{e,R}$.

The variations of the radiative thermal conductivity k_r with temperature for samples with and without activated carbons are presented in Fig. 7. Because $\sigma_{e,R}$ is almost independent of temperature for phenolic foams, from Eq. (2), the radiative thermal conductivity is proportional to the cubic temperature. And since $\sigma_{e,R}$ increases as the density, k_r decreases as the density increases. Comparing Figs. 2 and 7, radiation accounts for approximately 15% of total heat transfer for phenolic foams at room temperature.

IV. CONCLUSIONS

The thermal properties of phenolic foams, with or without activated carbon have been measured. Transmittance spectra were first taken using FTIR for samples of various densities. Extinction coefficient spectra were then obtained. The Rosseland mean extinction coefficients and the radiative thermal conductivities were calculated. Finally, the effective thermal conductivity under various temperature and conditions were measured using the heat flow meter method. Based on the results, the following conclusions can be drawn:

1. The extinction coefficient is slightly higher in the longer wavelength region for samples with and without activated carbon. The spectra have simi-

lar trends. Adding activated carbon seems to increase the extinction coefficient slightly.

2. The Rosseland mean extinction coefficient decreases only slightly as temperature increases from 200 K to 500 K. Increasing the insulation density increases the Rosseland mean extinction coefficient.
3. Radiative thermal conductivity decreases as the density increases, as a result of an increase in the extinction coefficient. Radiation accounts for approximately 15% of the total heat transfer for phenolic foams at near room temperature.
4. An optimum density exists for phenolic foams that has the minimum effective thermal conductivity. This optimum density is approximately 50 kg/m^3 .
5. In wet environments, it takes only two hours for the conductivity to increase about 20%.

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NOMENCLATURE

e	emissive power
k	thermal conductivity
L	thickness
n	refractive index
q	heat flux
T	temperature
T_n	Transmittance
ρ	reflectivity
σ	Stefan-Boltzmann constant

Subscript

b	blackbody
c	conductive
e	extinction
eff	effective
R	Rosseland mean
r	radiative
λ	spectral quantity

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酚醛樹脂發泡性隔熱材料之熱傳特性

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摘要

隔熱材料在工程上的應用極為廣泛。發泡性隔熱材由於具有成本低、加工方便、成型容易之優點，故應用甚為廣泛。酚醛樹脂發泡材因具有難燃及可耐較高溫度之特性，為近來漸受重視之隔熱材。本文主要針對原質與添加活性碳之酚醛樹脂發泡性隔熱材之熱傳特性作一探討。研究中使用符合 ASTM C518 認證標準之熱流計法等效熱傳導係數測定儀量測試片在不同條件下之等效熱傳導係數，並使用傅氏轉換紅外線光譜儀 (FTIR) 量測薄試片之穿透率，再利用比爾定律 (Beer's law) 以求得各波長下之消散係數，然後再對波長積分求其羅斯蘭平均消散係數，最後再利用擴散近似法理論求得輻射熱傳導係數。結果發現酚醛樹脂發泡材之熱傳導係數隨溫度之上升而增加。兩種材質發泡材均具有在某一密度時，會有最低的熱傳導係數 (k 值) 之特性。水氣對酚醛樹脂發泡材之隔熱性能的影響相當大。完全乾燥後之試片置於空氣中 2 小時，隔熱效果即可降低 20% 之多。密度愈大之試片，其羅斯蘭平均消散係數亦愈大，添加活性碳可略為增加消散係數。酚醛樹脂發泡材之輻射熱傳導係數與溫度之 3 次方成正比，且隨材料密度之增加而增加。熱輻射約佔總熱傳量之 15%。

關鍵詞：酚醛樹脂發泡材，隔熱材料，等效熱傳導係數，穿透光譜。