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TECHNICAL NOTE

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PREPARED BY W. Woodside | CHECKED BY AGW | APPROVED BY NBH

PREPARED FOR Fire Section, DBR | DATE July 1958

SUBJECT Thermal Conductivity of Mechanical Fire-Fighting Foams

The Fire Section has performed evaluation tests on 33-gallon chemical foam extinguishers and charges at the request of the Royal Canadian Air Force (1). The chief characteristic evaluated was the adhesive quality of chemical foam. The thermal insulating value of a layer of foam adhering to a surface is also of interest in connection with protection of aircraft from adjacent fires. The writer was asked to consider this aspect of the problem in relation to mechanical foam.

Due to the non-permanency of the foam layer, the conventional methods of thermal conductivity measurement cannot be easily applied. A calculation of the thermal conductivity of mechanical foam was therefore attempted.

The foam consists of a random distribution of small air cells in a liquid. The liquid is a mixture of approximately 94 per cent water and 6 per cent foaming agent. If the thermal conductivities and volume fractions of the two components (liquid and air) are known, the thermal conductivity of the composite foam may be estimated from the following formula from Russell (2):

$$k = \frac{k_s \left[P^{2/3} + k_s/k_g \ (1 - P^{2/3})\right]}{P^{2/3} - P + k_s/k_g \ (1 - P^{2/3} + P)} \qquad (1)$$

where k = thermal conductivity of foam

k_s = thermal conductivity of the liquid

k_g = thermal conductivity of air

P = air porosity of the foam, expressed as a fraction.

This equation assumes that the air cells are small enough (less than 1 cm in linear dimensions) to prevent the occurrence of heat transfer by convection. It has been used for the calculation of thermal conductivities of several high-porosity cellular thermal insulating materials such as foamed plastics, and has given results in good agreement with measured values (3).

The porosity P of the foam may be calculated from the expansion ratio. Thus if the expansion ratio is E, i.e. (E-1) parts by volume of air to 1 part of liquid, the porosity P is (E-1) E. For an expansion ratio of 10, the porosity of the foam is 0.90.

For the thermal conductivity k_s of the liquid, the thermal conductivity of water is assumed. Thus at 70°F, $k_s = 4.1$, and at 200°F, $k_s = 4.7$ Btu in./hr ft²°F.

The thermal conductivity of dry air is 0.180 at 70°F and 0.221 Btu in./hr ft²°F at 200°F. In a liquid foam as in other moist materials, however, there is an additional mechanism by which heat may be transmitted across the air cells. Under a temperature gradient, water vapour may evaporate from the warm face of an air cell, diffuse across the cell and condense on the cool face. In so doing, the latent heat of evaporation of the water is transferred across the air cell. This transfer of latent heat by distillation must be added to the normal thermal conductivity of dry air to obtain an effective conductivity k_g for the air cells in a liquid foam, i.e.

$$k_g = k_{air} + k_v \qquad (2)$$

The thermal conductivity component k_v due to distillation may be calculated from the following equation (3,4)

$$k_v = D.L.\frac{dp}{dT} \qquad (3)$$

where D = water vapour permeability of air, (perm in.)
L = latent heat of vaporization of water, (Btu/grain)
and dp/dT = rate of increase of saturated water vapour pressure with temperature (in Hg/°F)

At 70°F the water vapour permeability D of air is 120 perm in. (the perm in. is an abbreviation of the unit grains in./hr ft^2 in Hg). According to Krischer (3) the vapour permeability of air varies with temperature as follows

$$D = D_o \left(\frac{T}{273}\right)^{2.3} \qquad (4)$$

where T is absolute temperature °K. At 200°F therefore, the vapour permeability of air is 209 perm in.

The latent heat of vaporization of water is 1050 Btu/lb at 70°F and 978 Btu/lb at 200°F. The values of dp/dT at these two temperatures are 0.0256 and 0.489 in Hg/°F respectively.

Therefore at 70°F,

$$k_g = 0.180 + \left(\frac{120 \times 1050 \times 0.0256}{7000}\right) = 0.641 \text{ Btu in./hr ft}^2\text{°F}$$

and at 200°F

$$k_g = 0.221 + \left(\frac{209 \times 978 \times 0.489}{7000}\right) = 14.50 \text{ Btu in./hr ft}^2\text{°F}$$

These two values illustrate the very rapid increase with temperature of the effective thermal conductivity of an air cell whose walls are wet. At 32°F the effective conductivity of the air in such a cell is already twice the value for dry air, and at 140°F it is equal to the thermal conductivity of water. The application of equation (3) to the calculation of the effective conductivity of air cells in the foam neglects the presence of the foaming agent in the liquid mixture.

At 70°F, therefore, $k_s = 4.1$ and $k_g = 0.641$ and at 200°F $k_s = 4.7$ and $k_g = 14.5$ Btu in./hr ft^2°F. Substituting these values in equation (1), the thermal conductivity k of a foam with an expansion ratio of 10:1 is found to be

$$k = 0.90 \text{ Btu in./hr ft}^2\text{°F at 70°F}$$

$$\text{and } k = 13.0 \text{ Btu in./hr ft}^2\text{°F at 200°F}$$

The thermal conductivity of most thermal insulating materials is approximately 0.30 Btu in./hr ft^2°F. The thermal resistance R of a foam layer of thickness d may be calculated from $R = d/k$.

At temperatures below 140°F, increasing the expansion ratio will have the effect of lowering the thermal conductivity of the foam. Above this temperature the reverse effect will occur, and at 140°F the foam conductivity should be independent of the expansion ratio.

The thermal diffusivity α of a material is defined by the following relationship between its thermal conductivity k, its density ρ and its specific heat c :

$$\alpha = k / \rho c$$

The thermal diffusivity is a measure of the rate at which a temperature disturbance is propagated through the material. For the foam, the specific heat and density are easily obtained from the expansion ratio, since the heat capacity of the air in the foam may be neglected. For an expansion ratio of 10, c = 0.10 Btu/lb°F and ρ = 6.24 lb/ft^3. Using the above calculated values of k, the thermal diffusivity of the foam is obtained as follows:

$$\text{At } 70°\text{F. } \alpha = \frac{0.90}{12 \times 6.24 \times 0.10} = 0.12 \text{ ft}^2/\text{hr.}$$

$$\text{At } 200°\text{F. } \alpha = \frac{13.0}{12 \times 6.24 \times 0.10} = 1.73 \text{ ft}^2/\text{hr.}$$

Most thermal insulating materials have a diffusivity of the order of 0.01 ft^2/hr.

The very high values of the thermal conductivity and thermal diffusivity of the foam at 200°F are a result of the large heat transfer by distillation in the air cells at high temperatures. If a non-volatile liquid could be substituted for the water in the foam, thus suppressing the distillation mechanism so that $k_v = 0$, the foam would have thermal conductivities of 0.46 and 0.54 Btu in./hr ft^2°F at 70°F and 200°F respectively as compared with the above values of 0.90 and 13.0.

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