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THE OPTIMUM DIAMETER FOR A GLOBE THERMOMETER FOR USE INDOORS*

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Abstract—By applying currently recommended formulae for the heat transfer from spheres, and comparing results with up-to-date information about human response to air temperature and mean radiant temperature, it is shown that the optimum diameter for a globe thermometer, when used as an index of subjective warmth for people in buildings, is approximately 40 mm. The practical performance of such a globe thermometer is described.

INTRODUCTION

A GLOBE thermometer may be used within buildings for either of two functions:

(1) To estimate the mean radiant temperature of a room interior by using the reading in conjunction with a measurement of air movement and temperature; a large globe is preferred in this case because of its greater response to incident radiation.

(2) To assess the warmth of a room for human comfort. For this purpose the globe should be of a size which responds to radiation and convection in proportions similar to those for the human body. In order to obtain the relative responses of spheres of various diameters to convection and radiation, heat exchanges between a sphere and its surroundings have been examined using up-to-date information on convection. Comparison with current knowledge of human response shows that sphere diameters smaller than those currently in use are to be preferred for normal indoor conditions.

Convection and radiation from spheres

If an unheated object has a surface heat transfer coefficient of h_c (W/m^2°C) by convection, and a surface transfer coefficient of h_r (W/m^2°C) by radiation, it can be shown that it will acquire an equilibrium temperature equal to

$$T_g = \frac{h_c}{h_c+h_r} T_a + \frac{h_r}{h_c+h_r} T_s \qquad (1)$$

T_g is in this case the temperature of the globe thermometer (°C), T_a the temperature of the surrounding air (°C), and T_s the mean radiant temperature of the surrounding surfaces (°C). The globe temperature is therefore a weighted mean of the air temperature and the mean radiant temperature. It is convenient to describe the performance of the globe in terms of the ratio $\frac{h_r}{h_c+h_r}$, a value of 0.5 indicating equal response to changes in air temperature and in mean radiant temperature.

For a sphere small compared with its surrounding enclosure of high emissivity, the value of h_r is given with sufficient accuracy by the relation

$$h_r = 4\,E\,\sigma\,T^3. \tag{2}$$

where E is the emissivity of the surface of the sphere, σ is Stefan's constant and T (K) the mean of the temperature of the surface of the sphere and the mean radiant temperature of the surrounding enclosure.

For $E = 0.97$, $\sigma = 5.67\times10^{-8}$ W/m^2 K^4, and $T = 293$ K,

$$h_r = 5.53 \text{ W/m}^2\,^\circ\text{C}.$$

A recent correlation of forced convection data from spheres in air by HEY (1968) produces the recommended equation

$$(Nu) = 0.32(Re)^{0.6} \tag{3}$$

where Nu is the Nusselt number and Re the Reynolds number. The equation applies in the region $10^2 < Re < 10^5$, which well covers the usual range of air movement in rooms for spheres of diameter useful for globe thermometers. The value of Nu predicted by this equation is approximately 15% smaller than that obtained from the formula recommended by McADAMS (1954). The difference is attributable to the extra experimental data which Hey was able to include.

Expanding equation (3) we have

$$\frac{h_c\,D}{k} = 0.32\left(\frac{DG}{\mu}\right)^{0.6} \tag{4}$$

where D is the diameter of the sphere (m), k the thermal conductivity of the film of air surrounding the sphere (W/m°C), G its mass-velocity, which is the product of the density (kg/m^3) and its velocity (m/s), and μ the viscosity of the air (kg/ms). The convection coefficient h_c can therefore be calculated, and the value of the radiant response ratio $h_r/(h_c+h_r)$ obtained. This has been done for a range of air velocities and sphere diameters, and the result is shown in Fig. 1, for a temperature of 20°C.

Human response to radiation and convection

The human response data for conditions of natural convection or of very low air velocity, have recently been summarised by HUMPHREYS (1974). Physiological experiments on heat transfer from the surface of the body, and thermal comfort surveys and experiments, yield average weights of 0.54 and 0.46 for the air and the mean radiant temperature. The standard deviation of the mean of the various radiant response ratios was 0.02, which means that the value of $h_r/(h_c+h_r)$ lies between 0.42 and 0.50 with about 95% probability. The predominant air-movement for the experiments included in the summary was between 0.1 and 0.15 m/s. The zone contained by these boundaries is shown on Fig. 1. It suggests that a globe thermometer of about 40 mm would best describe the human response at these low air speeds.

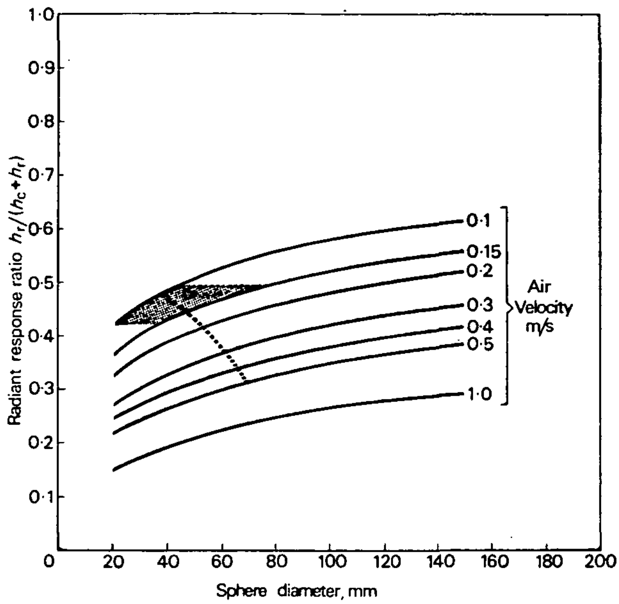

FIG. 1. The response to air temperature and mean radiant temperature of globe thermometers of diameter 20–150 mm for air speeds 0.1–1.0 m/s. The shaded zone indicates the human response at low air movement. The broken line shows the equivalent diameters using Fanger's equation.

This result can also be obtained from Fanger's 'Comfort Equation' (FANGER, 1970), for air velocity of 0.1 m/s. The radiant response ratio is 0.48 for sedentary people in clothing of thermal insulation 1 Clo, which is typical of indoor winter clothing. The size of the equivalent sphere is 38 mm. At higher air speeds the diameter of the equivalent sphere increases, as shown on Fig. 1. However, the comfort equation does not allow for the effect on the clothing insulation of air-penetration, which tends to increase the transfer of heat by convection as the air movement increases. There is very little experimental information on the effect of air movement on the insulation of normal civilian clothing. Regression analysis of the data obtained by Webb for subjects in tropical clothing in warm dry environments (NICOL, 1974) gives a radiant response ratio of only 0.1 at an air speed of 1.0 m/s. No doubt the clothing was rather more permeable to air movement than would be common for European clothing, but the result suggests that the effect of air movement on normal clothing should be further investigated. It could be that the smaller globe thermometer would be appropriate also for these higher air speeds.

For common indoor conditions, therefore, where the heat transfer from the surface of the clothing to the air is by natural convection, a globe thermometer of diameter about 40 mm would give the appropriate relative weight to air temperature and mean radiant temperature. At first sight a sphere of this size seems much too small to model human response. The explanation is chiefly that the surface of the clothed human body is not entirely convex. The effective area for radiation is thus considerably less than that for convection. The same ratio of convection to radiation can therefore be obtained from the much smaller, convex object.

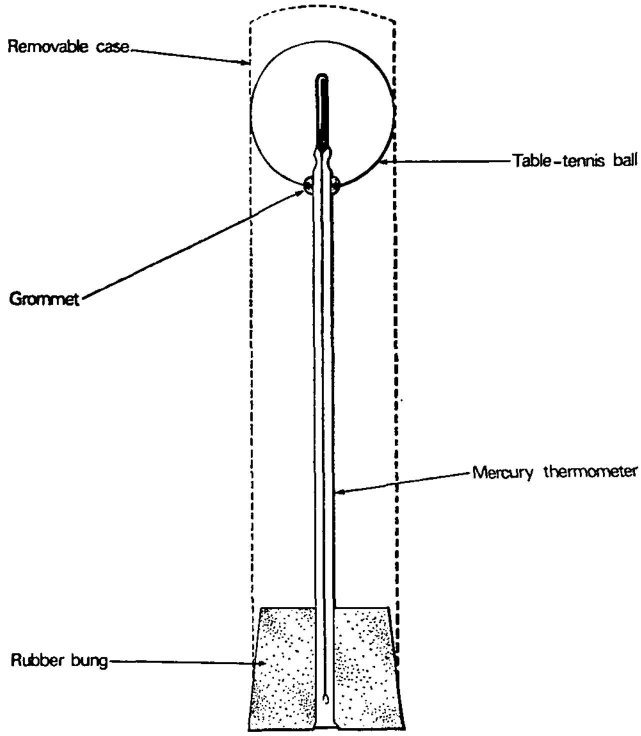

FIG. 2. Miniature globe thermometer (38 mm dia.).

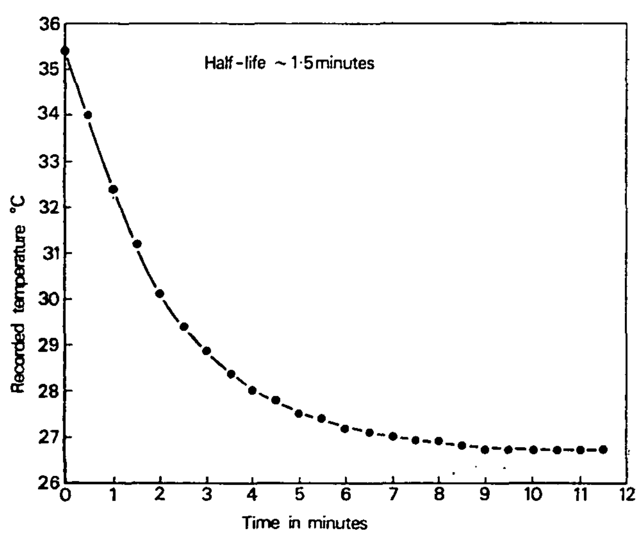

FIG. 3. Cooling curve for small globe thermometer.
(Matt-black table-tennis ball, rapid-response mercury thermometer.)

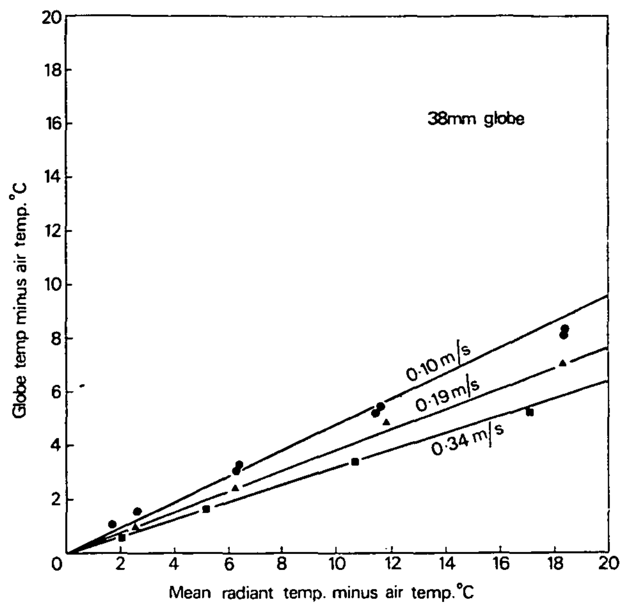

FIG. 4. Comparison of practical performance with theoretical predictions.
●, Experimental result, free convection. ▲, Experimental results, air speed 0.19 m/s. ■, Experimental result, air speed 0.34 m/s. The lines are those calculated using Hey's equation for h_c, and h_r = 5.53 W/m²°C.

Practical performance of a small globe thermometer

The advantages of a small globe thermometer are chiefly its rapid response and convenient size. Only when the difference between the air temperature and the mean radiant temperature is large will the difference between the reading of a small and a standard globe be appreciable. The difference would be about 0.6°C if $(T_a - T_s)$ were 5°C.

A small globe thermometer for practical use was constructed by inserting a mercury in-glass thermometer into a table-tennis ball, as shown in Fig. 2. The ball has a diameter of 38 mm, and was painted matt black. The thermometer was of the quick response pattern commonly used in sling hygrometers. The approach of the globe thermometer to equilibrium is shown in Fig. 3. The half-period is about 90 s, which is more than twice as rapid as the standard 6-in globe.

The radiant response ratio was then found experimentally, using a calibration booth whose walls could be maintained at a temperature above the air temperature, and in which the air movement could be varied. The results for free convection and for two fixed rates of air movement are shown in Fig. 4. The agreement with Hey's equation is satisfactory.

CONCLUSIONS

A small globe thermometer, about 40 mm in diameter, is more convenient and quicker to use than a standard 6-in globe, and is theoretically preferable for assessing the warmth of a room when the air-movement is slight.

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