THE GLOBE THERMOMETER IN STUDIES OF HEATING AND VENTILATION

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(With 4 Figures in the Text)

CONTENTS

I. Introduction

The two factors, radiation and convection, both play their part in influencing bodily warmth. The rate of heat loss from the body and the state of comfort or discomfort of the individual depend largely on the combined effects of these two factors. Many instruments have been designed which give a variety of combinations of such effects. Two such instruments used in this country are the kata-thermometer (Hill, 1919) and the eupatheoscope (Dufton, 1930, 1932). The cooling power of the kata-thermometer and the equivalent temperature recorded by the eupatheoscope both measure combinations of the cooling effects of radiation and convection.

Air currents probably exert much the same cooling effect on the eupatheoscope (a blackened cylinder, 22 in. high and $7\frac{1}{2}$ in. in diameter) as they do on the human body; but, because of its much smaller size, the kata-thermometer is particularly sensitive to air movement. Hill himself (1919, p. 48) using data obtained by Lefèvre, compared the rates of heat loss in still air and in wind of (*a*) the kata-thermometer, and (*b*) man and animals, and he showed that a strong air current has a very much greater effect on the rate of cooling of the kata than on that of, for example, a pigling. Various physical investigations have shown that the heat loss by convection is much influenced by the size of the cooling body (for bibliography see Fishenden and Saunders, 1932). Dufton (1930), dealing with the use of a special kata-thermometer for the estimation of equivalent temperature, referred to the excessive convection loss of the kata-thermometer due to its small dimensions. To make allowance for this excessive loss, Dufton used observations made on a similar thermometer with its bulb silvered.

https://doi.org/10.1017/S0022172400043242 Published online by Cambridge University Press

In a study of comfort in relation to the thermal environment, one wants ultimately to measure the combined effects of the various thermal factors, but it is highly desirable that one should be able to ascertain the influence of the separate factors concerned. For the measurement of radiation an ideal instrument is a sensitive radiation thermopile used in conjunction with a suitable galvanometer. Such apparatus is costly, however, and is not always available. It would be convenient, therefore, if some cheaper and simpler form of apparatus could be used for obtaining a reliable estimate of the amount of radiation at any point.

In a former paper (Bedford and Warner, 1933) we have shown that under steady conditions one can estimate the intensity of radiation by making parallel observations with two kata-thermometers, one kata being of the standard type and the other having a silvered bulb. For the measurement of radiation a Moll thermopile was used. The instrument was clamped on to a special stand provided with two graduated circles, one in a vertical and the other in the horizontal plane. The thermopile was pointed in turn to every part of the sphere surrounding the observation point, equal weight being thus given to every section of the sphere in calculating the mean intensity of radiation. Forty-six readings were taken for each such calculation. An alternative, and perhaps simpler, method of expressing the result was by what has been termed the "mean radiant temperature" (Barker, 1926, 1931; and Bohnenkamp and Pasquay, 1931) or "mean black body temperature" of the surroundings. This value is that uniform temperature at which a black surface would radiate with an intensity equal to the mean observed. Taking the thermopile values as standard, the estimates of mean intensity of radiation obtained from the kata-thermometer readings had an average error of less than 1 per cent., and the estimates of mean black body temperature had a mean error of 1·3° F.

Since the kata-thermometer is much influenced by changes in air velocity, it may be found that under industrial conditions, where the air movement is often somewhat variable, the error is greater than was found by us. It seemed probable that a larger instrument than the kata might furnish a more reliable estimate of radiation. It appeared to us that Vernon's globe thermometer might be adaptable for this purpose, and in this paper we can produce evidence that it is a reasonably reliable instrument for the estimation of the mean radiation from its surroundings.

II. The globe thermometer

Since the time of John Leslie various observers have used blackened spheres as indicators of radiant heat, but these have generally been filled with hot water, or otherwise heated. Leslie (1804) himself demonstrated the effects of radiation by using two 4-in. spheres of tin, one blackened and the other with a polished surface. Both were filled with warm water and the respective rates of cooling noted. Incidentally, it may be recalled here that Leslie also drew attention to the cooling effects of wind, and did in fact give an equation for the calculation of wind velocities from observations of the cooling rate of the polished sphere. These observations led Leslie to propose "a new and very simple kind of *anemometer*. It is in reality nothing more than a thermometer, only with its bulb larger than usual." Leslie then describes the method of observing the cooling time of the thermometer and proceeds: "The bulb of the thermometer might be more than half an inch in diameter, and may, for the sake of portability, be filled with alcohol, tinged, as usual, with archil."

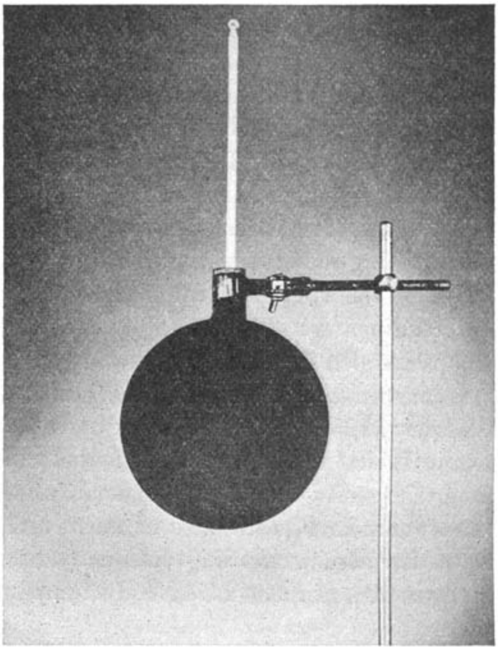

Fig. 1. The globe thermometer.

It was further suggested that extemporaneous calculation might be avoided by having a table engraved upon a scale to be applied to the tube of the thermometer. This is a remarkable forecast of the kata-thermometer, which was not introduced until over a hundred years after Leslie's book was published.

Aitken (1887) advocated the use of a blackened, hollow sphere of thin sheet metal, having a thermometer fitted to it with its bulb in the centre. He refers to readings with globes 15 and 40 cm. in diameter, and mentions that the size of the ball, if not too small, does not seem to affect the readings much.

The globe thermometer (Fig. 1), introduced by Vernon (1930, 1932*a*, *b*, 1933), is very similar to the globe used by Aitken. It consists of a hollow 6-in. copper sphere, coated with matt black paint, and containing an ordinary thermometer with its bulb at the centre of the sphere. Such copper globes are sold for use on ball valves, and it is only necessary to solder on to one of these a short tube to hold a cork pierced by the thermometer.

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There is no provision for heating the instrument; its temperature depends solely on the environment in which it is placed. If the surfaces which surround the globe are warmer than the air, the temperature recorded by the thermometer inside the globe will be above air temperature; and, conversely, with walls and other surroundings cooler than the air, the globe thermometer temperature will be below air temperature. Vernon (1932*a*) has shown that the globe reaches approximate equilibrium with its surroundings in about 15 min.

Both Aitken and Vernon introduced their globes as indicators of the effects of radiant heat on human comfort. This use of the instrument will be discussed in a later section. It is first desirable that the influence of radiation and convection on globe thermometer readings should be described.

When the globe thermometer is in equilibrium with its environment the effects of radiation and convection balance each other.

$$H_R = H_C \qquad \text{......(i)},$$

where H_R is the heat gain (or loss) by radiation; and H_C is the heat loss (or gain) by convection. By Stefan's law, the radiation gain may be expressed by the equation

$$H_R = E \, . \, \sigma \, (T_S^4 - T_G^4) \qquad \text{......(ii)},$$

where T_S is the absolute temperature of the surrounding surfaces, T_G is the absolute temperature of the globe surface, E is a numerical constant depending on the emissivity of the globe, and σ is Stefan's constant.

For a surface painted matt black the value of E is about 0·95. Using absolute temperatures on the Fahrenheit scale, and taking the value of σ as $1{\cdot}73 \times 10^{-9}$ (Fishenden and Saunders, 1932, p. 12), the value of H_R is expressed in B.Th.U. per sq. ft. per hour by

$$H_R = 0{\cdot}95 \times 1{\cdot}73 \times 10^{-9} \, (T_S^4 - T_G^4) \qquad \text{......(iii)}.$$

The equation for H_C, the convection loss, was obtained from a series of experiments in which a 6-in. copper globe, filled with hot water, was allowed to cool in air currents of known velocity.

Convection loss from a heated sphere

During these experiments the water in the globe was kept thoroughly mixed by bubbling through it a gentle stream of air which had previously passed through a wash-bottle containing water at the same temperature as that in the globe. The temperature of the water in the sphere was measured by means of thermojunctions, with an accuracy of about 0·02° F. Thus the total heat loss from the globe was determined with but small error. It is not implied that the surface temperature of the sphere was measured with such high accuracy. In each experiment the initial temperature of the globe was 100–110° F., or about 40° F. above air temperature, and cooling was continued until the temperature was only a few degrees above that of the air.

The range of air velocity covered was from 10 to 500 ft. per minute. The lowest velocity was that obtaining under quiet room conditions, with door and windows shut. For the higher velocities a small wind tunnel 17 in. in diameter was used. The globe was suspended in the current of air issuing from the mouth of the tunnel, and the air velocity was ascertained by means of the katathermometer, at the beginning and end of each experiment. For the measurement of air temperature a mercury thermometer, the bulb of which was screened from radiation by a layer of aluminium foil, was used. During each experiment periodic measurements of the radiation from the surroundings were made by means of a Moll thermopile. The radiation loss from the globe was calculated from equation (iii), and when this was subtracted from the total measured heat loss the remainder gave the convection loss.

As a check on the results thus obtained, further cooling experiments were made on a similar globe which had been silver-plated. Thermopile observations showed that this silver surface had an emissivity of about $8\frac{1}{2}$ per cent., so in the experiments with this globe the radiation loss was calculated by putting E equal to 0·085.

It was found that the convection loss was proportional to the square root of the air velocity, and to the difference between the temperatures of the globe and of the air. When v is the air velocity in feet per minute, t_g is the temperature of the globe, and t_a that of the air (both in °F.), the convection loss is given by

$$H_C = 0{\cdot}169\sqrt{v}\,(t_g - t_a) \qquad \text{......(iv).}$$

In Fig. 2, values of $H_C/t_g - t_a)$ have been plotted against $\sqrt{v}$. Each point on the diagram represents the mean values for a cooling experiment lasting from 2 to 5 hours. The points for the experiments on both blackened and silvered globes are fitted by the same straight line.

Equation (iv), from which the line in Fig. 2 is drawn, is linear in $(t_g - t_a)$. Actually, at low velocities the relation is not strictly linear, and there is a tendency for $H_C/\sqrt{v}$ to increase rather more rapidly than $(t_g - t_a)$ increases, but for the purpose of this paper it did not appear to be necessary to derive an equation of more complex form than that given above.

III. The estimation of radiant heat by means of the globe thermometer

In equations (iii) and (iv) the effects of radiation and convection on a 6-in. blackened copper sphere have been described. The heat balance of equation (i) can now be written

$$0{\cdot}95 \times 1{\cdot}73 \times 10^{-9}\,(T_S^4 - T_G^4) = 0{\cdot}169\sqrt{v}\,(t_g - t_a) \qquad \text{......(v).}$$

Combining the constants and transposing, we may write

$$T_S^4 \times 10^{-9} = T_G^4 \times 10^{-9} + 0{\cdot}1028\sqrt{v}\,(t_g - t_a) \qquad \text{......(vi),}$$

all temperatures being expressed in the Fahrenheit scale, and the air velocity in feet per minute.

If kata-thermometer observations are taken in conjunction with readings of the globe thermometer it is possible to calculate the radiation from the surrounding surfaces by applying equation (vi), for the air velocity can be calculated from the kata-thermometer readings. The value T_S represents what has already been described as the mean black body temperature, and the radiation intensity in B.Th.U. per sq. ft. per hour is readily calculated.

These radiation values refer to a spherical body placed at the observation point. The mean radiation thus ascertained is that from the sphere surrounding the globe thermometer, and since the area projected by the globe is the same

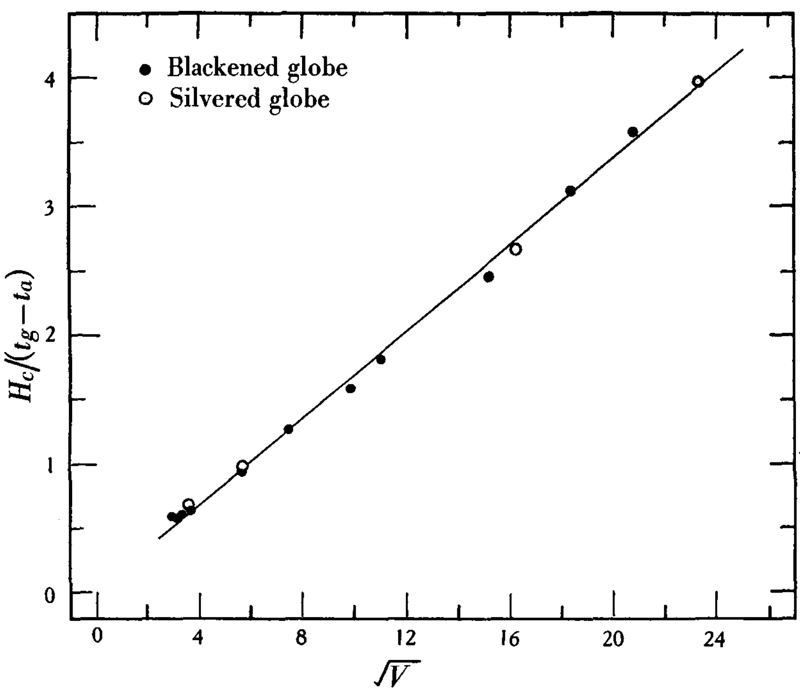

Fig. 2. Convection loss from 6-in. copper sphere in relation to air velocity.

in all directions, the mean radiation value is not influenced by the direction from which radiation reaches the globe. In considering a non-spherical body, however, such as a man or the eupatheoscope, the direction of the radiation should be taken into account, since the projection area of the body in different directions may vary considerably. Attention has previously been drawn to this fact by Bohnenkamp and Ernst (1931), and by Hallett (1931), but, as the point may assume some importance where the bulk of the radiation is from a localised source, *e.g.* a gas fire, it is desirable that it should be mentioned again here.

When many data are to be dealt with the evaluation of an expression such as equation (vi) is tedious, and much labour can be saved by the use of a nomogram. Radiation values can be quickly read off from the nomogram in

Fig. 3 by the following method. Through the appropriate points on scales *A* and *B* a line is struck to cut scale *C*. The intersection with scale *C* gives the value of $(T_S{}^4 - T_G{}^4) \times 10^{-9}$. From this intersection another line is drawn

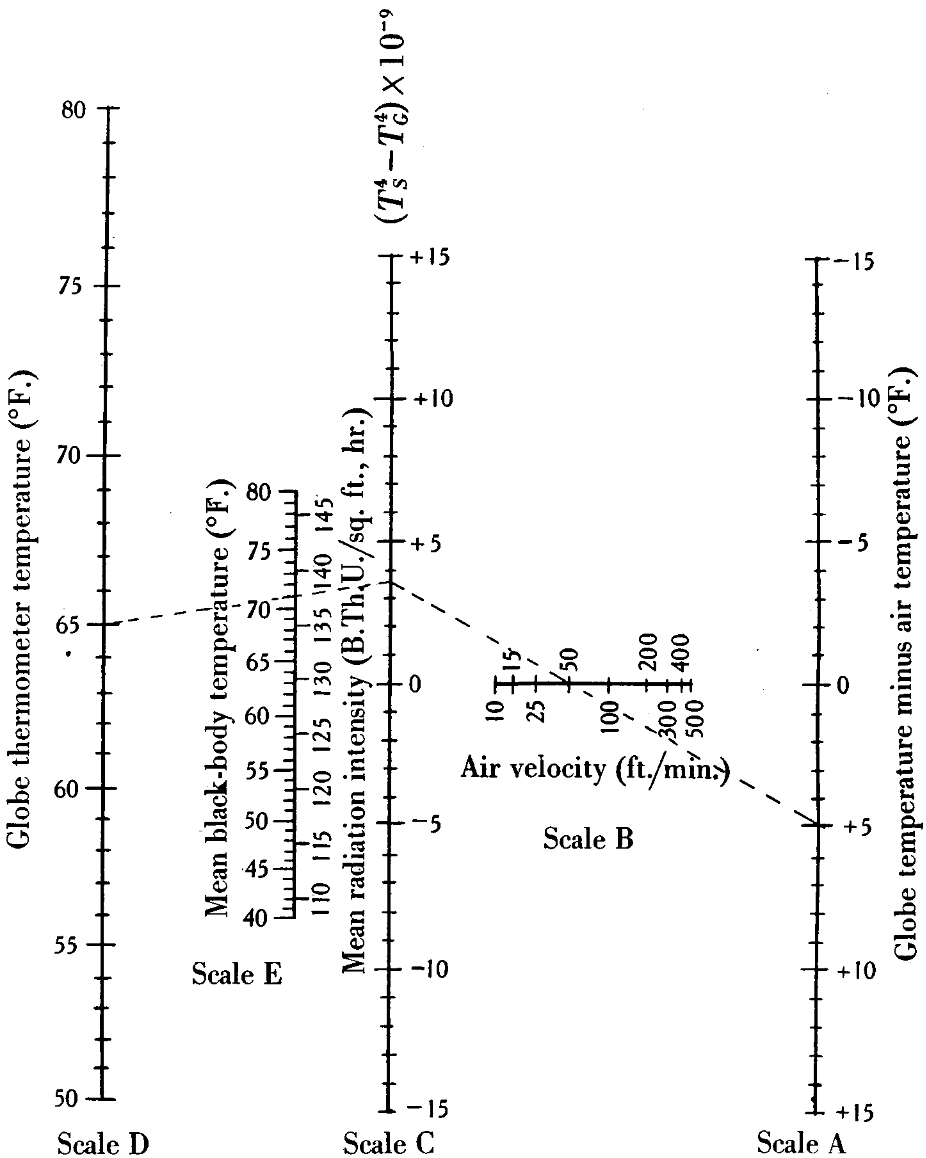

Fig. 3. Chart for the estimation of radiation from globe thermometer readings.

through the appropriate point on scale *D*. The intersection with scale *E* gives either the mean black body temperature or the radiation intensity in B.Th.U. per sq. ft. per hour.

As an example, suppose a set of observations have given an air temperature of 60° F., a globe thermometer reading of 65° F., and an air velocity of 50 ft. per min. The value of $(t_g - t_a) = 5°$. Drawing the lines as described in the preceding paragraph, and as shown by a broken line in Fig. 3, it is found that the mean black body temperature is 71° F., and the radiation intensity corresponding to this is 137·5 B.Th.U. per sq. ft. per hour.

For the purpose of testing the reliability of this method of estimating radiation we have made use of observations made by us in a recent investigation in factories with various systems of heating and ventilation. At each observation position readings of a silvered kata-thermometer (Bedford and Warner, 1933) and of a globe thermometer were taken, and the mean radiation was measured by means of a Moll thermopile. Air temperatures were measured by means of a mercury thermometer, screened with aluminium foil. The air velocity was calculated from the kata-thermometer and air temperature observations. From these data it was possible to calculate the radiation, using equation (vi), and, to test the accuracy of the method, the direct thermopile measurements being taken as standard.

For a total of 221 sets of observations the mean error of estimation of radiation intensity was 1·2 B.Th.U. per sq. ft. per hour, or, in terms of mean black body temperature, the average error was only 1·2° F. The observations covered a considerable range of conditions; in some cases the surrounding surfaces were much warmer than the air, and in others distinctly cooler.

Table I. *Errors of estimation of mean black body temperature from globe thermometer observations.*

Mean black body temperature (thermopile value) *minus* air temperature ° F.	Number of observations	Average error made in estimating mean black body temperature from globe thermometer observations ° F.
−6·0 to −4·1	4	1·23
−4·0 to −2·1	13	1·06
−2·0 to −0·1	19	0·59
0 to 1·9	76	0·94
2·0 to 3·9	57	1·48
4·0 to 5·9	30	1·16
6·0 to 7·9	11	1·50
8·0 to 9·9	5	1·20
10·0 or over	6	3·08

The mean error of estimation is fairly constant over the whole range of conditions, as will be seen from Table I, where, in order to make clear the relation between the temperatures of the air and of the surrounding surfaces, the radiation intensity is referred to in terms of mean black body temperature. It is only in the extreme group, where the difference between the air and mean black body temperatures was over 10° F., that the error is appreciably above the average of 1·2° F. The observations in this group were all made in close proximity to gas-heated appliances which were constantly being moved to and fro: the conditions were variable, and closer agreement could not be expected.

The foregoing observations appear to justify the conclusion that the globe thermometer is a practicable instrument for the estimation of radiant heat.

IV. The estimation of equivalent temperature

As was mentioned at the beginning of this paper, the eupatheoscope gives a combined measure of the effects of radiation and convection. This instrument is essentially a black-painted hollow copper cylinder, electrically maintained at 75° F. (approximately the mean surface temperature of a clothed person in a comfortable environment), the heat loss from which is recorded in degrees of *equivalent temperature*. The equivalent temperature of an environment is that temperature of a uniform enclosure in which, in still air, the eupatheoscope would lose heat at the same rate as in the environment. The scale of equivalent temperature does not extend above 75° F.

The Inter-Departmental Committee on Terminology, etc., in Heating and Ventilation Research, set up by the Medical Research Council and the Department of Scientific and Industrial Research, express the view that for the ordinary conditions of artificial heating, where humidity effects are negligible and ventilation does not vary between wide limits, the eupatheoscope may be regarded as a standard instrument (Building Research Board, 1931). It is further stated that eupatheoscope readings of equivalent temperature may be taken as a basis for comparison of readings taken with other instruments or combinations of instruments.

Outside the laboratory it is not always practicable to use the eupatheoscope, as it frequently happens that no electricity supply is available. Some other method of estimating equivalent temperature is therefore desirable. For this purpose Dufton (1933*a*, 1933*b*) has utilised special kata-thermometers with a cooling range of 75·5–74·5° F. Readings are taken with a pair of such kata-thermometers, one kata having its bulb silvered, and the other having a blackened bulb, and from these readings the equivalent temperature is calculated. Over a wide range of conditions Dufton (1933*b*) found that the equivalent temperature as estimated from kata-thermometer readings had a probable error of only $\frac{3}{4}$° F. The mean error of estimation in his twenty-six recorded observations is 0·82° F.

The fact that the globe thermometer yields a reliable estimate of radiation suggested that this instrument might be used with the kata-thermometer for estimating equivalent temperature.

It was first necessary that we should have some information as to the separate effects of radiation and air movement on the heat loss from the eupatheoscope. No equation relating radiation and convection in this way has been recorded, but from a few data published by Dufton (1930, 1933*a*) it

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has been possible to estimate an equation which seems to give fairly good results. This equation is

$$\text{Equivalent temperature} = 30 + 0{\cdot}6t_s - (75 - t_a)\,(0{\cdot}4 + 0{\cdot}07\sqrt{v}) \quad \ldots\ldots\text{(vii)},$$

where t_a is the air temperature in ° F.;
t_s is the mean black body temperature in ° F.; and
v is the air velocity in feet per minute.

From the results of other workers, cited by Fishenden and Saunders (1932), it would appear that the index of v should be nearer 0·7 than the value 0·5 used in equation (vii), but, with low velocities such as those commonly met with in ordinary buildings, no serious error is introduced by using $\sqrt{v}$.

Using the notation given in the last paragraph, and putting t_g for the globe thermometer reading, we have, as a close approximation to equation (v),

$$t_s = t_g + 0{\cdot}169\sqrt{v}\,(t_g - t_a) \quad \ldots\ldots\text{(viii)}.$$

Substituting for t_s in equation (vii), we have

$$\text{Equivalent temperature} = 0{\cdot}4t_a + 0{\cdot}6t_g + \sqrt{v}\,(0{\cdot}101t_g - 0{\cdot}031t_a - 5{\cdot}25) \quad \ldots\ldots\text{(ix)}.$$

The chart given in Fig. 4 has been constructed from equation (ix). In order to ascertain the equivalent temperature it is only necessary to draw a line between the points on the air temperature and globe thermometer temperature scales. The equivalent temperature is then shown at the intersection of this line with the appropriate air velocity line. For example, suppose we have an air temperature of 60° F., an air velocity of 50 ft. per min., and a globe thermometer reading of 65° F. From the chart we read that the equivalent temperature is 59·1° F. The chart does not extend beyond an air velocity of 100 ft. per min., as we have no knowledge that equation (vii) gives satisfactory results beyond this value.

In the factory observations referred to earlier in this paper, we regularly recorded the equivalent temperature as given by the eupatheoscope or by 75° kata-thermometers, kindly lent by Mr Dufton, and for fifty-nine observations we have both the eupatheoscope reading and the kata-thermometer estimate. These data have been used as standards with which to compare estimates of equivalent temperature made from globe thermometer readings. With the globe thermometer readings we have used air velocities calculated from readings of silvered kata-thermometers.

Under experimental conditions Dufton's estimates of equivalent temperature from kata-thermometer readings had a mean error of 0·82° F. In the fifty-nine sets of observations in which we were able to compare kata-thermometer estimates against eupatheoscope readings, the average error was found to be 1·22° F. When it is remembered that these observations were made in factories where the conditions were subject to variation, this result must be regarded as very satisfactory. For the same group of observations we have estimated equivalent temperatures from globe thermometer readings, using the chart of Fig. 4. Compared with the corresponding eupatheoscope readings, these estimates had a mean error of 1·08° F. Altogether we had 100 eupatheoscope readings with which to compare globe thermometer

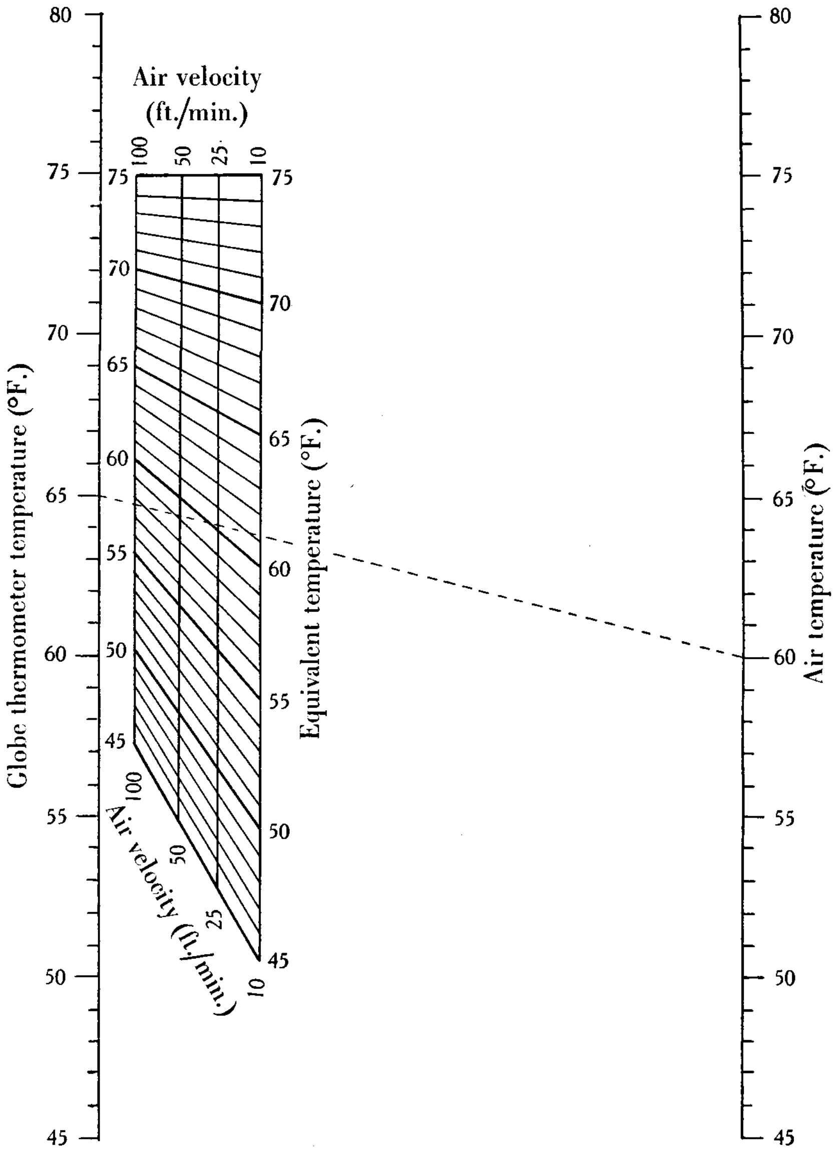

Fig. 4. Equivalent temperature in terms of air velocity, air temperature and globe thermometer temperature.

estimates of equivalent temperature, and over this group the mean error of estimation was 1·18° F.

Our estimates of equivalent temperature from globe thermometer readings

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were slightly more accurate than those calculated from readings of 75° kata-thermometers.

In many observation positions the eupatheoscope could not be used, and estimates of equivalent temperature from kata-thermometer readings had to be relied upon. A total of 179 such observations were made, and for this group the average difference between the kata-thermometer and globe thermometer estimates was 2·0° F. This group includes a number of observations which were made in positions where the radiation was by no means constant. Under steady conditions the agreement would undoubtedly have been much closer.

A possible source of error in the estimation of equivalent temperature lies in the fact that the globe thermometer takes no account of the direction of radiation. An illustration may be drawn from data given by Vernon (1932*a*, p. 102; 1932*b*, Table II), in which a comparison is made of various conditions of radiation which induced a feeling of comfortable warmth in two subjects. These observations may be divided into two groups, (*a*) those in which the subjects sat at various distances from a gas fire, and (*b*) those made in rooms heated by ceiling panels or by an anthracite stove. The radiation from the gas fire was of greater intensity than that from the anthracite stove or the ceiling panels, and it was on the horizontal component of the radiation reaching the subjects that this greater intensity had most effect. Thus, by virtue of the relatively large vertical surface of the subjects, they were exposed to a greater average radiation intensity than was the globe thermometer with its spherical surface. On this account the globe thermometer would tend to give too low an estimate of the equivalent temperature. This is evident when equivalent temperatures are calculated from Vernon's data. The five sets of observations in the rooms heated by the anthracite stove or ceiling panels give equivalent temperatures of 57·4–58·8° F., with an average of 58·1° F. On the other hand, the calculated values for persons seated at distances of 9, 7, and 6 ft. from a gas fire were respectively 57·3, 56·0, and 55·2° F.

This source of error in the estimation of equivalent temperature is only likely to be of importance where there is considerable difference between the horizontal and vertical components of the radiation.

V. THE GLOBE THERMOMETER AS AN INDEX OF COMFORT

Aitken (1887) pointed out that measurements of solar radiation made with a blackened bulb *in vacuo* may indicate a very strong solar radiation, and yet we may feel chilly; or they may indicate a comparatively low radiation effect, and we may feel warm. He went on to say that, while wind has but little effect on the solar radiation thermometer, it has a most powerful influence in checking the heating effect of the sun on our own bodies. He advocated the use of his hollow metal sphere as a means of obtaining more definite information about the climate of the place. Aitken showed that, with the same vacuum thermometer reading, the temperature registered by the hollow

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globe varied according to the wind force. From the reading of the hollow ball and that of the vacuum thermometer he calculated a ratio which he found to vary inversely as the cooling effect of the wind. He then multiplied this *ratio by the difference between the air temperature and the temperature* of the blackened globe, and thus obtained a figure which he took to represent the combined effects of solar radiation and wind. He claimed that values thus calculated represented more nearly the climatic conditions than those given by any other method in use.

Vernon introduced his globe thermometer as a means of indicating the combined effects of radiation and convection as they influence the human body. The temperature recorded by the globe thermometer, which we have referred to simply as the "globe thermometer temperature," is termed by Vernon (1932*a*, 1932*b*) the "radiation-convection-temperature," and the excess (or deficit) of the globe thermometer temperature over the air temperature is termed by him the "effectual radiation temperature." Vernon claims that this excess or deficit indicates the "effectual radiation" to which the human body is subjected (1932*a*, p. 96). This claim is not justified, for, as Aitken and Vernon (1932*a*, p. 100) themselves have shown, and as we have demonstrated in this paper, under constant conditions of radiation and air temperature the temperature of the globe thermometer is much influenced by air movement. Therefore unless allowance is made for the effects of air movement the globe thermometer cannot be used to measure radiation, but only to indicate whether the mean radiant temperature is above or below air temperature.

Under calm air conditions (air velocity 12–20 ft. per min.) Vernon found that his subjects were comfortable when the globe thermometer temperature was about 62° F., even though the air temperature ranged from 49·3 to 61·7° F. It would appear from these data that with the low velocities which are generally found under ordinary industrial conditions, the globe thermometer reading is a good index of comfort. When there is any appreciable draught, however, the globe thermometer fails. For instance, when Vernon's subjects, wearing dark clothing, sat out of doors exposed to the sun's radiation they were comfortable with globe thermometer temperatures of 69·5–78·3° F. instead of the 62° F. found to be comfortable indoors. The air velocity out of doors was 93–275 ft. per min., as compared with 12–20 ft. per min. in the indoor observations.

In order to allow for this effect of wind, Vernon calculated corrected kata-thermometer cooling powers, using globe thermometer temperatures instead of shade air temperatures. These corrections make too much allowance for air movement, for out of doors Vernon's subjects were comfortable with corrected cooling powers of 7·3–8·8, while indoors they required a cooling power of only 6.

By itself the globe thermometer is inadequate as an index of the thermal environment. For example, when the air and surrounding surfaces are at the same temperature, the globe thermometer will record air temperature whatever

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the air velocity. Again, if the surroundings are cooler than the air, the globe thermometer reading will be below air temperature, but with air temperature and radiation constant the temperature of the globe will approach more nearly to that of the air as the air velocity increases. Thus, of two environments, that which would cause the greater cooling of the human body would give the higher temperature reading on the globe thermometer.

VI. CONCLUSIONS

The considerations set out in the last section lead to the conclusion that readings of the globe thermometer taken alone are unreliable as indications of the combined effects of the thermal environment on human comfort.

It has been shown, however, that if in addition to globe thermometer readings the air temperature and the cooling power of the silvered kata-thermometer are determined, much valuable information can be obtained. Such observations are readily made, and from them one can ascertain with considerable accuracy:

(*a*) the equivalent temperature;

(*b*) the air velocity;

(*c*) the mean radiation intensity (or the mean black body temperature); and

(*d*) the cooling power of the ordinary kata-thermometer.

Of these data (*a*) and (*c*) can be calculated by the methods described in this paper; (*b*) is calculated from the appropriate equation given by us in a previous paper (1933); and by using (*c*) one can determine (*d*) from data set out in that paper.

Thus, in addition to obtaining a reliable estimate of the equivalent temperature, one is also enabled to assess the thermal factors which go to make up that combined measure. This is an advantage when the equivalent temperature shows any departure from the accepted standard of comfort, for information is then available which will serve to indicate the direction in which a remedy should be sought.

In this paper we have advocated the use of silvered kata-thermometers for the measurement of air velocities. It has been shown by us (1933) that, where the surroundings are at a temperature much different from that of the air, estimates of air velocity made from readings of the ordinary kata-thermometer are subject to considerable error.

The results of this study demonstrate the utility of the globe thermometer, and suggest that it should be of considerable value in studies of heating and ventilation.

VII. SUMMARY

The effects of radiation and convection on the globe thermometer have been studied.

Equations have been obtained, and alignment charts constructed, for the calculation of mean radiation intensity and of equivalent temperature from readings of the globe thermometer, air temperature and air velocity.

The accuracy of these methods has been tested on observations made under industrial conditions. Taking direct thermopile observations as the standard, the mean radiation intensity values calculated from globe thermometer readings had an average error of 1·2 B.Th.U. per sq. ft. per hour. With eupatheoscope readings as standard, equivalent temperature estimates had a mean error of 1·2°.

It is concluded that, while globe thermometer readings alone are unreliable as indications of the effects of the thermal environment, valuable results can be obtained by using the instrument along with an ordinary thermometer and a silvered kata-thermometer.

Acknowledgments. The laboratory experiments in this investigation were performed in the Department of Industrial Physiology of the London School of Hygiene and Tropical Medicine. We wish to thank the authorities of the School for the facilities afforded to us. Our thanks are also due to Mr A. F. Dufton for the loan of 75° kata-thermometers.

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(*MS. received for publication* 21. VII. 1934.—Ed.)