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THERMAL RADIATION AND ITS EFFECT ON
THE HEATING AND COOLING OF
BUILDINGS

by

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PREFACE

The prediction of the energy exchange between the exterior surfaces of a building or other construction and the outdoor environment cannot readily be reduced to a simple basis. The dominant weather elements which affect this energy exchange are sunshine, air temperature and wind. In addition, the shape and orientation of the building and its relationship to the ground and surrounding objects, as well as the absorptivity and emissivity characteristics of the surfaces involved enter into the problem. Additional complication is provided by the effects of rain, condensation and evaporation. Fortunately these latter effects are not always involved and so, as is done in this report, they are usually disregarded. Even without them the problem is difficult enough.

The normal meteorological readings which are taken do not adequately describe the weather for purposes of calculating its effect upon the surface energy exchange, particularly when sunshine is involved. Even if all the individual factors are measured there remains the problem of recombining these multiple streams of variables in the calculation. There is, fortunately, a way of achieving some simplification; a combined factor called sol-air temperature can be used so that it becomes necessary only to deal with a single stream of data.

This report discusses the sol-air temperature concept and the ways in which values of sol-air temperature can be obtained. A series of special measurements are proposed, and the instruments required to make them are considered. Accurate records of sol-air temperature would be of great assistance in the calculation of the heat gains of buildings in summer.

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ABSTRACT

The sol-air temperature concept is very useful when calculating the heat exchange at the outside surfaces of buildings. To be accurate the sol-air temperature must take account of the exchange of long wave-length thermal radiation as well as the solar radiation. It must not be based on a surface heat transfer coefficient which assumes that convective and radiative heat transfer are always in the same direction and in the same proportions. The expression for the sol-air temperature given by Parmelee and Aubele appears to be the most satisfactory:

$$t'_{sa} = t_a + \frac{\alpha I_s - \epsilon \cdot \Delta I_L}{h_c + h_r}$$

where $\Delta I_L = \nabla T_a^4 (0.45 - 0.33 \sqrt{P_w})$

and $h_r = \epsilon \cdot \nabla (T_s^4 - T_a^4) / (T_s - T_a)$

The sol-air temperature defined in this way can be used to calculate the heat exchange at the surface of a building by

$$q = (h_c + h_r)(t'_{sa} - t_s)$$

The sol-air thermometer in the form described by Mackey and Wright will not, in general, indicate the correct sol-air temperature for a wall of different size even though the material and exposure are the same. Thus it is recommended that sol-air temperature should be calculated from data on the incident thermal radiation, the emissivity and absorptivity of the wall surface and the convection heat transfer coefficient at the surface. The apparatuses for measuring these data are discussed.

THERMAL RADIATION AND ITS EFFECT ON THE HEATING AND COOLING OF BUILDINGS

by

D. G. Stephenson

To estimate accurately the maximum heating and cooling load for any building whose walls and roof have an appreciable heat storage capacity, it is necessary to account for the damping (and phase lag) in the daily fluctuations in heat flow caused by this capacity. At the outside surfaces of a building there is heat transfer by convection, the absorption of incident radiation of all wave-lengths, and the emission of long wave-length radiation. For non-steady-state heat flow determinations it is a great simplification if all these heat transfer processes can be replaced by one equivalent process. This is equally true whether the determination is being done mathematically or by an analogue. The advantage of using a fictitious temperature and surface coefficient to replace the parallel convection and radiation processes has been recognized for many years. More than one method of determining the fictitious temperature and thermal resistance of the surface film has been suggested. The following discussion examines these methods in relation to the phenomena involved, as a basis for decisions as to the most acceptable way of describing the thermal influence of weather upon buildings.

Nomenclature

| | |
|------------|--|
| A and B | constants defined by equation 22 |
| E | e.m.f. developed by thermopile |
| h | combined convection and radiation surface coefficient = $h_c + h_r$ |
| h_c | surface coefficient of heat transfer by convection |
| h_r | radiation coefficient of heat transfer $= \epsilon \cdot \nabla \cdot (T_s + T_a)(T_s^2 + T_a^2)$ |
| i_v, i_h | angles of incidence of direct solar radiation on vertical and horizontal surfaces respectively |
| I_s | intensity of short wave radiation, direct and diffuse combined |
| I_L | intensity of long wave radiation |

$$\Delta I_L = \sqrt{\cdot} \cdot T_a^4 - I_L$$

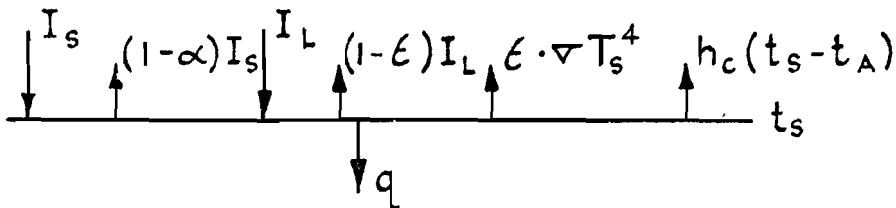
| | |
|-------------------------|---|
| k' | thermal conductance of heat meter |
| ** k | thermal conductivity of air |
| ℓ | characteristic length; over-all length of a surface in the direction of the air flow past the surface |
| P_w | partial pressure of water vapour in the atmosphere at ground level. in. mercury |
| q | heat flux into the surface |
| * T_a, t_a | temperature of the ambient air |
| T_f | film temperature = $(T_a + T_s)/2$ |
| T_r | radiometer temperature |
| T_s, t_s | surface temperature |
| t_{sa} | sol-air temperature as defined by Mackey and Wright (equation 7) |
| t'_{sa} | sol-air temperature defined by Parmelee and Aubele (equation 12) |
| V | air velocity parallel to surface outside the boundary layer |
| λ, ϵ | emissivities of surface for short and long wave radiation respectively |
| λ', ϵ' | emissivities of radiometer surfaces for short and long wave radiation respectively |
| λ'', ϵ'' | emissivities of surface of earth for short and long wave radiation respectively |
| V | Steffan's constant |
| ** ρ | density of air |
| ** μ | viscosity of air |

* T indicates absolute temperature and t temperature °F.

** k, ρ, μ are all evaluated at T_f

Sol-Air Temperature

The idea of using a fictitious temperature which would combine the effects of heat transfer by radiation and convection was first proposed by Mackey and Wright (1). In their first paper it was called equivalent outdoor air temperature (in subsequent papers - sol-air temperature) and was defined as: " - - - the temperature of the outdoor air which, in contact with a shaded wall, would give the same rate of heat transfer and the same temperature distribution through the wall as exist with the actual outdoor air temperature and incident solar radiation."



The heat balance at the surface gives

$$q = h_c(t_a - t_s) + \alpha I_s + \epsilon (I_L - \sigma T_s^4) \dots\dots\dots 1$$

but $\alpha I_s + \epsilon (I_L - \sigma T_s^4) = \text{Net Exchange} \dots\dots\dots 2$

By the definition of sol-air temperature

$$q = h(t_{sa} - t_s) \dots\dots\dots 3$$

where h is the combined convection and radiation coefficient

for a shaded wall. If it is assumed that $I_L = \sigma T_a^4$

i.e., that the surroundings radiate as a black body at air temperature.

$$\epsilon \cdot \sigma (T_a^4 - T_s^4) = h_r(t_a - t_s) \dots\dots\dots 4$$

where $h_r = \epsilon \cdot \sigma (T_a^4 - T_s^4) / (T_a - T_s) \dots\dots\dots 5$

$$\doteq 4 \epsilon \cdot \sigma T_f^3 \dots\dots\dots 5a$$

Then $q = (h_c + h_r)(t_a - t_s) + \alpha I_s \dots\dots\dots 6$

If $h = h_c + h_r$ equations 3 and 6 can be combined to give

$$t_{sa} = t_a + \frac{\lambda I_s}{h} \dots\dots\dots 7$$

Equation 7 is the equation for sol-air temperature given by Mackey and Wright. They pointed out (2) that equation 3 indicates that t_s will equal t_{sa} if $q = 0$, i.e. a

perfectly insulated surface will be in thermal equilibrium with its surroundings when it is at the sol-air temperature. They use this observation as the basis for suggesting that sol-air temperatures can be obtained directly by measuring the temperature of thin slices of building materials, supported by materials of very low thermal conductivity and exposed to ambient wind and radiation conditions. The sol-air temperature obtained in this way will not give the correct value of q if used in equation 3 unless the value of h for the surface in question is the same as that which existed at the surface of the sol-air thermometer. This equality of h is very unlikely since h_c is dependent on the size of the surface; being higher for small surfaces.

In all the foregoing discussion it has been assumed that $I_L = \nabla T_a^4$. Parmelee and Aubele (3) compared the data on I_L which they obtained, with previous work

by Dines and Dines, and showed that the incident long wave radiation from a cloudless sky is related to dry bulb temperature and the partial pressure of water vapour by

$$I_L = \nabla T_a^4 (0.55 + 0.33 \sqrt{P_w}) \dots\dots\dots 8$$

where P_w is partial pressure of water vapour at ground level in inches of mercury.

Parmelee and Aubele use equation 8 to derive an expression for sol-air temperature.

They let $I_L = \nabla T_a^4 - \Delta I_L \dots\dots\dots 9$

where $\Delta I_L = \nabla T_a^4 (0.45 - 0.33 \sqrt{P_w}) \dots\dots\dots 10$

If this expression for I_L is substituted into equation 1 it gives

$$q = h(t_a - t_s) + \lambda I_s - \epsilon \cdot \Delta I_L \dots\dots\dots 11$$

Then equations 3 and 11 give

$$t'_{sa} = t_a + \frac{\lambda I_s - \epsilon \cdot \Delta I_L}{h} \dots\dots\dots 12$$

The difference between t'_{sa} and t_{sa} as given by equation 7 is

$$t'_{sa} - t_{sa} = - \frac{\epsilon \cdot \Delta I_L}{h} \dots\dots\dots 13$$

This indicates that the error in sol-air temperature, which is caused by the assumption that the surroundings radiate as a black body at air temperature, is $\epsilon \cdot \Delta I_L / h$. For a surface seeing only a clear sky, ΔI_L has the value indicated by equation 10, while for a completely overcast sky, ΔI_L is zero.

If sol-air temperature is calculated from equation 12 it is practically independent of surface temperature. h_c and h_r are each dependent on the film temperature but have temperature derivatives of opposite sign (Appendix 1).

The importance of ΔI_L was shown by Parmelee and Aubele by the following example:^L

The 1951 ASHVE Guide gives as the 24-hour average of sol-air temperature for a horizontal roof seeing a clear atmosphere $t_{sa} = 109.1^\circ\text{F}$.

when $\lambda/h = 0.25$.

This assumed $\Delta I_L = 0$, but

$$\Delta I_L = \sqrt{T_a^4 (0.45 - 0.33 \sqrt{P_w})} \dots\dots\dots 10$$

Taking $T_a = 540^\circ\text{R}$ as a 24-hour average and $P_w = 0.50$ in. mercury (Dew Point = 59°F .)

$$\Delta I_L = 147 \times 0.22 = 32 \text{ Btu/hr. ft}^2$$

if $\epsilon = 0.90$ and $h = 4.0$

$$t'_{sa} - t_{sa} = - \frac{0.90 \times 32}{4.0} = -7.2^\circ\text{F}.$$

For an indoor air temperature maintained at 78°F throughout the period, the heat gain using the value of t'_{sa} will be

77 per cent of what it would be using t_{sa} as given in the Guide.

Thus the sol-air temperature should be calculated by equation 12 rather than by equation 7. All the data needed for this calculation are not known accurately, so in a later section apparatuses are described which could obtain these needed data. However, until more experimental data are available the following values should be used:

(1) Surface coefficient h

The ASHAE Guide (1956) recommends for design calculations $h = 6.0$. This is based on test data obtained from 1 ft. square samples at a mean temperature of 20°F. with a wind velocity of 15 m.p.h.

(2) ΔI_L

This quantity should be calculated by equation 10 taking account of outside temperature and humidity.

(3) I_s

The values of I_s for use in equation 12 should be the sum of I_s the direct and the diffuse solar radiation which falls on the surface. Data on I_s for a horizontal surface are available for most first class weather stations. Few data exist for I_s incident on a vertical surface, but an estimate can be made on the basis of the horizontal surface data. The relative intensities of the direct and diffuse radiation on a horizontal surface have been measured by Patterson (4) at Toronto. He found that 12 per cent of I_s (horizontal) is due to diffuse radiation from a clear sky; and for very hazy conditions it could be as much as 30 per cent.

Thus for clear conditions, Direct Solar = $0.88 I_s$ (horizontal). If i_h is the angle of incidence of the direct beam on the horizontal surface and i_v the angle of incidence

on a vertical surface, the direct solar on the vertical surface is

$$\text{Direct Solar (vertical)} = \text{Direct Solar (horizontal)} \left(\frac{\cos i_v}{\cos i_h} \right) \dots 14$$

It is sometimes assumed that the diffuse sky radiation comes uniformly from all parts of the sky so that any vertical surface will receive half as much as a horizontal surface. This is convenient for present purposes but for highest accuracy the data in the 1952 Guide P. 267 should be used. Then, neglecting reflection from the ground, the short wave

radiation on a vertical surface is

$$I_s \text{ (vertical)} = \left(\frac{0.88 \cos i_v}{\cos i_h} + 0.06 \right) I_s \text{ (horizontal)} \dots\dots 15$$

This factor must be increased to allow for the radiation reflected from the ground surface in front of the vertical wall. This reflected radiation is $(1 - \lambda'')$ I_s (horizontal)

where λ'' is the absorptivity of the ground surface. The ground reflected radiation is uniformly distributed to the upper hemisphere.

Therefore,

$$I_s \text{ (vertical)} = \left(\frac{0.88 \cos i_v}{\cos i_h} + 0.06 + \frac{1 - \lambda''}{2} \right) I_s \text{ (horizontal)} \dots\dots 16$$

$\cos i_v$ and $\cos i_h$ are conveniently tabulated in the 1952 ASHVE Guide on pages 269 and 270.

(4) λ and ϵ

The reflecting powers for the surfaces of many building materials have been measured by Beckett (5). The absorptivity λ is equal to one minus the reflecting power of the surface. In the absence of any other data it is suggested that Beckett's values for surfaces which are similar to those in question should be used.

The value of ϵ for most commonly used materials is listed in McAdams (6) and can be used with confidence.

Radiation Measuring Instruments

The thermal radiation which falls on the surface of a building can be divided into two classes:

- (1) Solar radiation with wave-length less than $2\frac{1}{2}$ microns.
- (2) Long wave-length radiation with wave-length greater than $2\frac{1}{2}$ microns.

The solar radiation has its maximum intensity at a wave-length of $\frac{1}{2}$ micron while the black body radiation from terrestrial sources has its maximum at wave-lengths around 10 microns.

Since many surfaces have quite different absorptivities for long and short wave-length radiation it is necessary to measure the intensities of the radiation in each class separately.

Pyrheliometers

The U.S. Weather Bureau measures solar radiation at many locations in the United States and after testing all the available instruments they have accepted the Eppley thermoelectric pyrheliometer as the most suitable for their needs (7). The construction details and characteristics of this type of pyrheliometer are described in a paper by T.H. MacDonald (8) and are only briefly summarized here.

The receiving surfaces of the Eppley pyrheliometer are concentric flat metal rings exposed in a common plane. One ring is coated with magnesium oxide and the other with lamp black. Because of the difference in absorptivity of these coatings the rings attain different equilibrium temperatures when exposed to sunlight. The output of the instrument is the e.m.f. of a platinum-rhodium (90-10) and gold-palladium (60-40) thermopile with junctions on the two rings. The receiving surfaces are protected by a glass bulb. The glass used for this bulb has an almost constant transmission factor for solar radiation.

One peculiarity of the instrument is that the e.m.f. per unit of radiation flux decreases as the temperature increases so that a calibration is necessary at several temperatures in the range usually encountered. The Weather Bureau tests also indicated that the calibration depends on the angle which the receiving surfaces make with the horizontal.

When radiation has an angle of incidence at the receiving surfaces of less than 60° , the instrument output is proportional to the normal intensity times the cosine of the angle of incidence. For incidence angles greater than 60° the output becomes less than the cosine response (at 80° the response is down to 80 per cent of cosine response).

Hand (7) gives useful advice on the proper care of the instruments and the Weather Bureau method of standardizing their instruments against a Smithsonian pyrheliometer.

Actinometer

When Eppley pyrheliometers are used to measure solar radiation continuously it is necessary to have a standard available against which the Eppleys may be checked. The U.S. Weather Bureau uses a Smithsonian pyrheliometer as its standard. The Meteorological Branch of the Department

of Transport has found that a good thermopile radiometer is a more convenient working standard and has sufficient stability to require comparison with a primary standard only once a year. The Kipp company of Delft, Holland makes a radiometer which is suitable for use as a working standard.

Net Exchange Radiometer

The heat meter type of radiometer developed by Gier and Dunkle (9) can be used to measure the net exchange of energy at a surface. The heat meter element is placed parallel to the surface so that one side of the heat meter is exposed to the same incident radiation as the surface while the other side is exposed to the radiation reflected by the surface and the radiation emitted by the surface. Thus the difference in the radiant energy incident on the two sides of the heat meter is the amount of thermal energy exchanged between the surface and its surroundings.

In the following sections the relationship is derived between this net exchange and the e.m.f. developed by the heat meter thermopile.

Figure 1 shows schematically the heat exchange at each surface of the heat meter.

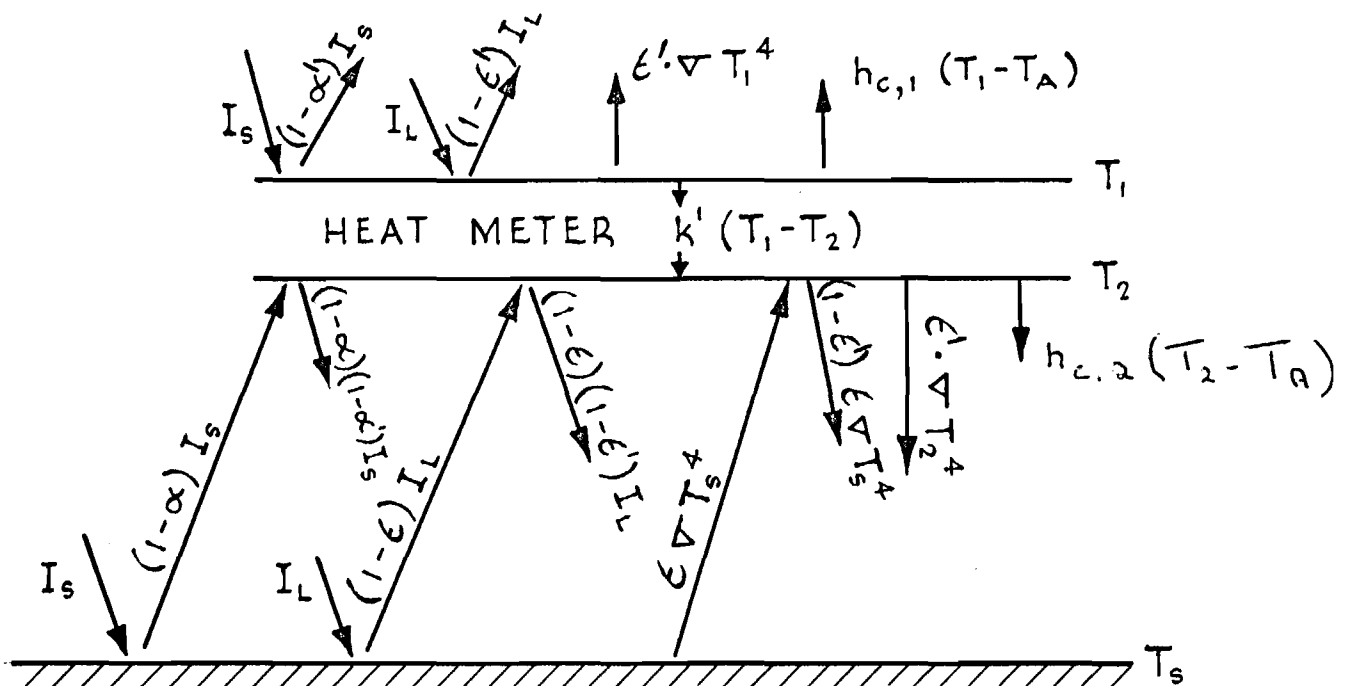


Figure 1.

The heat balance at surface 1 is

$$\alpha' I_s + \epsilon' I_L = k'(T_1 - T_2) + \epsilon' \cdot \sigma \cdot T_1^4 + h_{c,1} (T_1 - T_a) \dots 17$$

and at surface 2

$$\alpha' (1-\alpha) I_s + \epsilon' (1-\epsilon) I_L + \epsilon' \cdot \nabla (\epsilon \cdot T_s^4 - T_2^4) + k'(T_1 - T_2) = h_{c,2} (T_2 - T_a) \dots 18$$

If these are subtracted it gives

$$\alpha \cdot \alpha' \cdot I_s + \epsilon \cdot \epsilon' (I_L - \nabla T_s^4) = 2k'(T_1 - T_2) + \epsilon' \cdot \nabla (T_1^4 - T_2^4) + h_{c,1} (T_1 - T_a) - h_{c,2} (T_2 - T_a) \dots 19$$

If $\alpha' = \epsilon'$ i.e. both surfaces of the heat meter are assumed

to be grey; and $h_{c,1} = h_{c,2} = h_c$ this simplifies to

$$\alpha' \cdot (\text{Net Exchange}) = (T_1 - T_2) \left\{ 2k' + h_c + 4 \cdot \epsilon' \cdot \nabla T^3 \right\} \dots 20$$

$$\text{or Net Exchange} = (T_1 - T_2) \left\{ \frac{2k' + h_c}{\alpha'} + 4 \cdot \nabla T^3 \right\} \dots 21$$

where T is the average of T_1 and T_2 .

The e.m.f. developed by the thermopile is

$$E = (T_1 - T_2) (A + BT) \dots 22$$

Therefore

$$\text{Net Exchange} = E \left\{ \frac{\left(\frac{2k' + h_c}{\alpha'} + 4 \nabla T^3 \right)}{A + BT} \right\} \dots 23$$

The quantity in brackets is the calibration constant which obviously depends on k' , α' , h_c and T and is only valid when

$\epsilon' = \alpha'$, (i.e. when the surfaces of the heat meter are 'grey') and when $h_{c,1} = h_{c,2}$.

If the surfaces are not grey the calibration constant will depend on the relative intensities of the long and short wave-length radiation which is incident on the meter. Similarly if $h_{c,1}$ does not equal $h_{c,2}$ the calibration constant will depend on $T_1 - T_a$ and $T_2 - T_a$.

A radiometer of the Gier and Dunkle type is manufactured commercially by the Beckman and Whitley Co. The heat meter surfaces are painted with Fullers Flat Black Decoret paint. This has $\alpha' = 0.94$ approx. and $\epsilon' = 0.86$, so that the calibration of this instrument with sunlight will be somewhat in error for the combined long and short wave

radiation which falls on the surface of the earth. Secondly, this instrument employs a small fan to circulate air over both surfaces of the heat meter element but there is no way to check easily that $h_{c,1}$ is equal to $h_{c,2}$ nor to adjust the

air flow to make the film coefficients equal if they are found to be different. It is important that the air velocity over the heat meter be high enough so that wind conditions will not change h_c appreciably. The Beckman and Whitley radiometer is influenced by winds at an angle to the direction of the air movement caused by the fan.

An improved radiometer of this same type has been described by Suomi, Franssila and Islitzer (10) which differs from the Beckman and Whitley apparatus in two important ways. These are:

- (1) provision is made to check the equality of $h_{c,1}$ and $h_{c,2}$ and to adjust the air streams to make them equal if they are found to be different.
- (2) the absorptivity of the surface for long and short wave lengths is made more nearly constant than a surface covered by Fullers Flat Black Decoret, by covering parts of it with a lead-carbonate paint. This absorbs only 6 per cent of solar energy but has a high absorptivity in the infra-red.

This instrument has been proved capable of measuring the net radiation to within an accuracy of 2 per cent, except, for very small values of net radiation.

A net exchange radiometer can be used to measure total hemispherical radiation by simply placing it so that one side sees a surface of known temperature and emissivity. Then the total hemispherical radiation is the sum of the net exchange and the radiation emitted and reflected by the surface. This last quantity is easily calculated when the temperature and emissivity of the surface are known.

A Method of Measuring h_c , ΔI_L and I_s

When calculating sol-air temperature by equation 12 it is necessary to know h_c , ΔI_L and I_s along with other data. The apparatus outlined here would provide data from which these three quantities could be determined for a test wall.

An experimental determination of h_c appears desirable because of its importance when calculating sol-air temperature, and because the values currently used were not

determined from measurements made on actual walls. Additional experimental data for ΔI_L and I_s applicable to vertical surfaces are also needed since most previous work has been restricted to horizontal surfaces.

Figure 2 shows a laminated bakelite heat meter attached to the outside surface of a wall surrounded by a large sheet of bakelite of the same thickness. The surface of the heat meter and its surround are painted the same colour so that the surface temperature will be uniform over the central portion. A net exchange radiometer measures the net radiant energy exchanged at the surface.

If heat flow into wall is q

$$h_c = \frac{\text{Net Exchange} - q}{t_s - t_a} \dots\dots\dots 24$$

The temperature at the middle of the heat meter is measured by a thermocouple. The surface temperature differs from this only by a small increment depending on q and the bakelite thermal conductivity so that an accurate surface temperature can be obtained.

These data will also give a value for the surface sol-air temperature

$$t'_{sa} = t_s + q/h \dots\dots\dots 25$$

where $h = h_c + h_r$

If a pyrliometer is mounted with its receiving surfaces parallel to the surface, the quantity ΔI_L can also be determined from its output and the other data.

Since

$$t'_{sa} = t_a + (\Delta I_s - \epsilon \cdot \Delta I_L)/h \dots\dots\dots 12$$

then $\epsilon \cdot \Delta I_L = h(t_a - t_s) + \Delta I_s - q \dots\dots\dots 26$

Thus with this apparatus it is possible to obtain h_c , ΔI_L and

I_s . If Δ and ϵ are known for a wall surface it is then possible to calculate the sol-air temperature for the surface when exposed to the same conditions as the test wall. This ability to obtain sol-air temperature for any wall from one set of measured data is an improvement on the sol-air thermometer which gives sol-air temperature for only one surface.

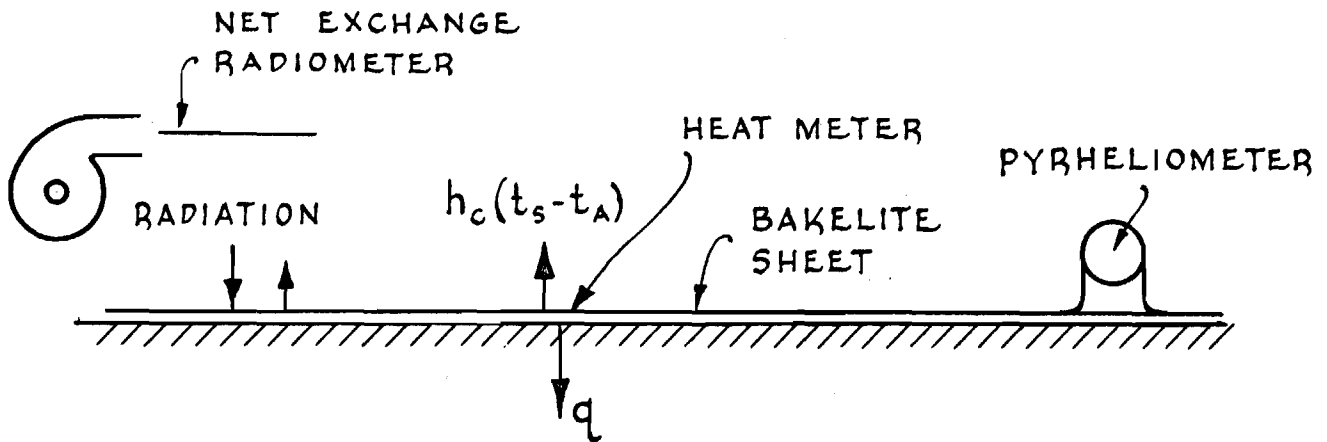


Figure 2

An Apparatus to Measure the Solar Absorptivity of a
Wall Surface

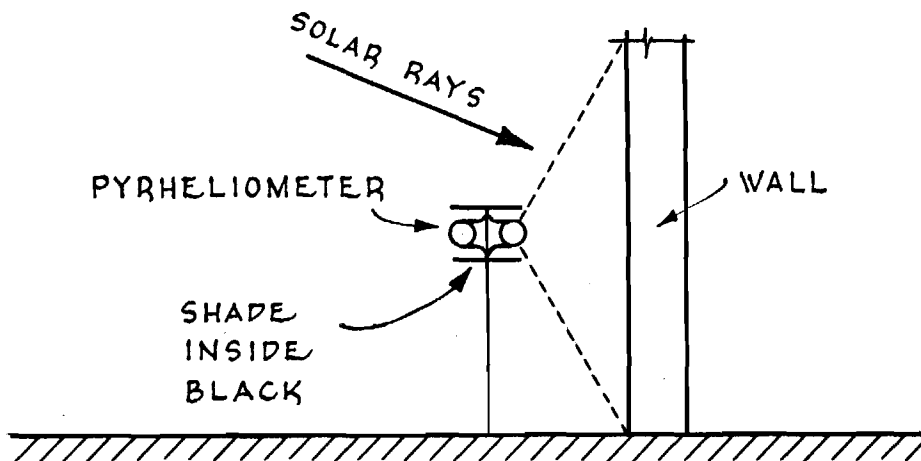


Figure 3

Two pyrhemliometers mounted back-to-back on a stand which can be rotated should be able to measure the reflectivity of a surface for solar radiation. One pyrhemliometer measures the intensity of the radiation incident on the wall while the other measures the reflected solar radiation. The ratio of the reflected to the incident is the surface reflectivity, or one minus the absorptivity.

By rotating the unit so that the pyrhelimeters are interchanged, the unit will give a second value of absorptivity. The mean of these two values will be independent of the pyrhelimeter constants. The short shading tube defines the angle of view of the pyrhelimeters. This is necessary since it is assumed that only reflected radiation is incident on one pyrhelimeter, and without the shade it would see some sky as well as the wall.

An Apparatus to Measure the Low Temperature Emissivity
of a Wall Surface

If a jacketed thermopile radiometer is placed against a wall surface and the radiometer temperature is slowly raised from a value below the wall surface temperature to some value above it, the thermopile output vs. radiometer temperature will be as shown in Fig. 5.

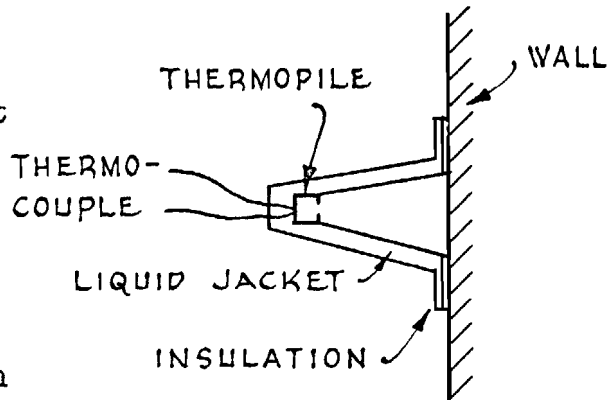


Figure 4

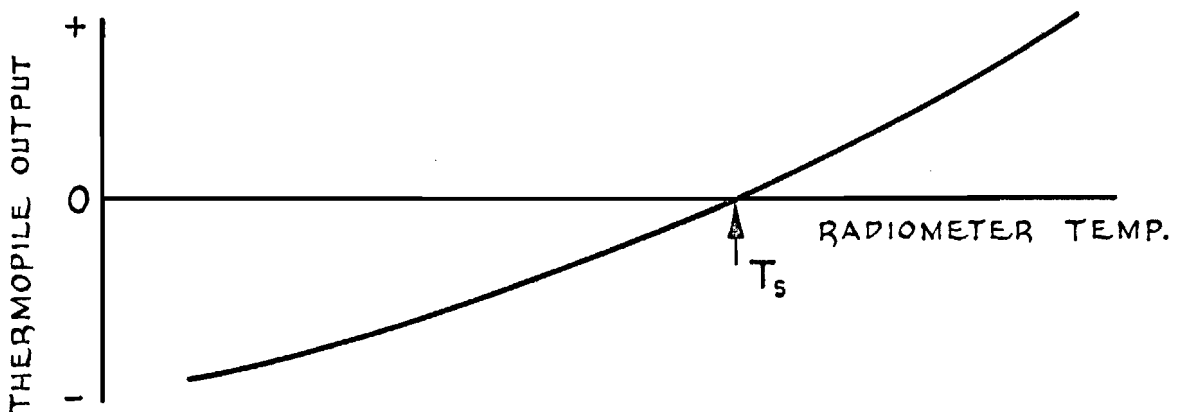


Figure 5

The temperature at which the output is zero is the wall surface temperature; and for radiometer temperatures other than the wall temperature, the output is

$$\text{Output} = F(T_r) \cdot \epsilon \cdot (T_s^4 - T_r^4) \dots\dots\dots 27$$

$$\text{therefore} \left[\frac{\partial}{\partial T_r} (\text{Output}) \right]_{T_r = T_s} = \phi(T_s) \times \epsilon \dots\dots\dots 28$$

Thus if the radiometer is sighted on a surface where ϵ is known (e.g. a black small angle cone $\epsilon = 0.99$), one series of experiments will suffice to determine $\phi(T_s)$.

Then, if the radiometer is sighted on a surface of unknown ϵ , ϵ can be found from equation 28 since both T_s and

$$\left[\frac{\partial}{\partial T_r} (\text{Output}) \right]_{T_r = T_s} \text{ are measurable.}$$

This apparatus differs from the usual long wave-length emissivity apparatus in that it measures the surface temperature as well as the emissivity. Thus it can be used on walls without altering them in any way.

Conclusions

- (1) The use of sol-air temperature is a very convenient way of accounting for heat exchange by radiation and convection when calculating the non-steady-state heat transfer to and through a building wall.
- (2) A small sol-air thermometer will not indicate the correct sol-air temperature for a large wall even though they have the same surface and exposure.
- (3) It is more practical to obtain the data needed to calculate sol-air temperature than to try to measure sol-air temperature for many different wall surfaces. The data needed are: outside air temperature; the intensity of solar and long wave-length radiation incident on a surface of any orientation; the absorptivity of the surface for solar and long wave-length radiation; and the convection heat transfer coefficient appropriate for the surface.
- (4) A calculated sol-air temperature must take account of the long wave-length radiation which is exchanged at the outside surface of a building. This cannot be done by assuming that the surroundings radiate as a black body at outside air temperature.
- (5) All of the needed data are not now known with sufficient accuracy to permit the calculation of reliable sol-air temperatures.

- (6) A continuous record of the sol-air temperature for the surface of the earth would be very useful. A degree-day correlation of frost penetration based on sol-air temperature degree-days should be more reliable than a similar correlation based on outside air temperature alone. Similarly sol-air temperature data would be useful when studying permafrost regions and the effect of changing the surface emissivity.

General Remarks

Each surface of a building has a different sol-air temperature vs. time relation; and since it is unlikely that all surfaces will experience the seasonal extreme value during one 24-hour period, one cannot say exactly, when the maximum heating or cooling load will occur. It is only by making a heating- or cooling-load calculation for a whole building, taking account of infiltration, solar gain through glass, and the latent cooling load if any, for each time when a maximum might occur, that the actual maximum for a season can be found.

If an outside air temperature is chosen, which is exceeded only 5 per cent of the time during the average cooling season and if complete data are available for every day on which this particular temperature is exceeded, a complete cooling-load calculation can be made for any building for each of these days. If a cooling load is chosen so that half the previously calculated loads are above it and half below, one can then say that this load will be exceeded only $2\frac{1}{2}$ per cent of the time during an average cooling season. The reliability of this approach is improved as the number of calculations and cooling seasons is increased.

This method of arriving at the heating or cooling load for a building is only practical if the data are on punched cards so that the calculations can be made on a computing machine.

The data needed for the periods when maximum heating and cooling requirements can be expected are the hourly average values of: the sol-air temperature for each outside surface of a building, wind speed and direction, outside air temperature, dew point temperature, and solar radiation incident on the window surfaces.

Recommendations

1. It is suggested that the Division expand the program for meteorological observations to include the data necessary to calculate h_c , I_s , and ΔI_L for the exterior surfaces of buildings.

The objects of this study would be twofold:

- (a) To determine if all the needed data can be inferred with sufficient accuracy from the observations which are now being made by the Meteorological Branch.
- (b) If additional observations are found to be necessary the DBR station could be the prototype for the new instrumentation which might be set up at some meteorological stations.

2. In view of the large number of data which will be obtained from even one station and the amount of computation necessary to reduce these data to the required form, it is recommended that methods of automatic data recording and processing be investigated.

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Appendix I

Variation in Outside Surface Coefficient with Film Temperature

The outside film coefficient h is given by

$$h = h_c + h_r$$

Therefore

$$\frac{\partial h}{\partial T_f} = \frac{\partial h_c}{\partial T_f} + \frac{\partial h_r}{\partial T_f}$$

For forced convection where the air flow over the surface is turbulent the convection coefficient h_c is given by

$$\frac{h_c \cdot l}{k} = 0.03 \left(\frac{V \cdot \rho \cdot l}{\mu} \right)^{0.80}$$

Thus

$$\frac{d h_c}{h_c} + \frac{d l}{l} - \frac{d k}{k} = 0.80 \left\{ \frac{d V}{V} + \frac{d \rho}{\rho} + \frac{d l}{l} - \frac{d \mu}{\mu} \right\}$$

When T_f is the only variable and has a value of about $500^\circ R$

$$\frac{d h_c}{h_c} = \frac{\partial h_c / \partial T_f}{h_c} \cdot d T_f$$

$$\frac{d k}{k} = \frac{\partial k / \partial T_f}{k} \cdot d T_f \div + 0.0018 d T_f$$

$$\frac{d \rho}{\rho} = \frac{\partial \rho / \partial T_f}{\rho} \cdot d T_f = - 0.0020 d T_f$$

$$\frac{d \mu}{\mu} = \frac{\partial \mu / \partial T_f}{\mu} \cdot d T_f = + 0.0016 d T_f$$

Therefore

$$\begin{aligned} \frac{\partial h_c / \partial T_f}{h_c} &= 0.0018 + 0.8 (- 0.0020 - 0.0016) \\ &= - 0.0011 (F^\circ)^{-1} \end{aligned}$$

$$h_r \div 4 \cdot \epsilon \cdot \nabla \cdot T_f^3$$

so $\partial h_r / \partial T_f \div + 12 \cdot \epsilon \cdot \nabla \cdot T_f^2$

For $T_f = 500^\circ\text{R}$, $\epsilon = 1.0$

$$\partial h_r / \partial T_f = + 0.00519 \text{ Btu/hr. ft.}^2 (\text{F}^\circ)^2$$

$$h_r = 0.86$$

If $h = 6.0$, $h_c = 5.14$

$$\text{so } \partial h_c / \partial T_f = - 0.0011 \times 5.14 = - 0.00565$$

$$\text{and } \partial h / \partial T_f = - 0.00565 + 0.00519 = - \underline{0.00046}$$

If $h = 5.0$, $h_c = 4.14$

$$\text{so } \partial h_c / \partial T_f = - 0.0011 \times 4.14 = - 0.00455$$

$$\text{and } \partial h / \partial T_f = - 0.00455 + 0.00519 = + \underline{0.00064}$$