MEASURING DEVICE FOR THE DETERMINATION OF THE EMISSIVITY OF NON TRANSPARENT SURFACES

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INTRODUCTION

The energy balance in glasshouses is influenced to a great extent by the emissivity of materials inside the glasshouse. In view of the lack of good instruments in the past, researchers had to calculate with emissivity data available in normal literature.

Once the radiation thermometer had been developed, it was possible to measure surface temperatures without touching the object. From the point of view of pure measuring technique it was necessary to know the emissive power of the radiant surroundings. Moreover, it became topical to know the emissivities of a steadily growing number of plastic foils because of their use in energy saving methods.
Because of the lack of suitable measuring equipment we were obliged to construct an instrument, with which it would be possible to determine the emissive powers of different materials in the "long-wave domain" of the spectrum.

RADIATION

Planck's law describes the heat radiation of a black body as a function of temperature and wavelength. At a temperature of $300^{\circ}K$ a black body radiates approximately 14% of its energy in the long wave domain from 0 to 8 µm, 38% in the 8 to 14 µm domain and 22% in the 14 to 20 µm domain.
If one would confine oneself either to materials which absorb all non-reflected radiation in a very thin layer, or to foils possibly having a small transmission, one would be able to calculate the radiation exchange with the aid of Plank's universal law of radiation also for non-black bodies.
To achieve this, one has to use factors for the transmission $\tau(\lambda\ \zeta)$, the reflection $R(\lambda, \zeta)$, the absorption $A(\lambda, \zeta)$ and the emission (λ, ζ).
(Wavelength : λ; angle to the perpendicular: ζ).

For technical calculations on heating systems, it is important, to know the total energy flow, which requires integration of the wavelength and direction. Mean values have been used for this purpose for the absorption, reflection, etc.
In principle, this is only possible, if "gray" diffuse surfaces are involved, i.e. R and A are independent of wavelength and direction. These problems can be avoided more or less by taking absorption and reflection as functions of temperature.

An effort has been made to find measuring equipment, suitable to determine the mean emissivity of a surface at temperatures which are normal for glasshouses and buildings, in order to be able to carry out technical calculations on heating systems.
The usual way to describe the radiant heat flux Q from a surface as a function of temperature (T) and emissivity (ε) is as follows:

$$Q = \varepsilon . Cs . (T/100)^4$$

where: $Cs = 5.77 \left[W/m^2 . deg^4\right]$

POINTS TO BE CONSIDERED BEFORE DEVELOPMENT

A main issue for the development of the measuring arrangement was the consideration that the emissivity of the object should be determined without having to measure the temperature of the object itself. It is not advisable to choose a method in which the temperature of the object has to be measured, because this is very difficult and often causes the destruction of the object.

THE PRINCIPLE OF MEASUREMENT

This instrument operates on the principle of comparing the radiation intensities from an object when:

(a) a surface with a high ε value participates in the radiation exchange (black)

(b) a surface with a low ε value participates in the radiation exchange (Al-foil).

The ambient temperature should be higher than the temperature of the object; the radiation from the object is measured with a radiation thermometer. Depending on whether the black- or the Al covered plate is placed underneath the kettle, the heat reflected by the kettle will vary, as will the reading of the radiation thermometer.

The emissivity of the object can be calculated by using these values.

DESCRIPTION OF THE MEASURING ARRANGEMENT

The supporting frame work of the instrument was constructed of welded pipes. The movable base plate, half of which is painted black and the other half covered with aluminium foil, is fitted on top of this structure. This base plate can be moved easily underneath the kettle, so that depending on the position of the plate, the kettle has a base plate covered with black non-reflectant paint or with Al foil (bottomview, Fig. 3).

The kettle can be filled with water and kept at the right temperature by means of an electric immersion heater. A small pump maintains an even temperature all over the kettle, especially at the cone, inside the kettle. The temperatures of the kettle wall and of the cone are measured also with thermocouples.

If the base plate is correctly positioned under the kettle, one of the two holes in the base plate should be within the field of view of the radiation thermometer. The radiation thermometer has been positioned in such a way, that its axis forms an angle of approximately 8° with the perpendicular on the base plate.

The value of 8° has been chosen to minimize errors due to specular reflection of radiation from the radiation thermometer by the surface of a test object with a smooth surface.

FORMULA FOR THE CALCULATION OF ε

(see Fig. 4).

Kettle: temperature T_k, emissivity ε_k, reflectivity R_k
Plate : temperature T_p, emissivity ε_p, reflectivity R_p
Object: temperature T_m, emissivity ε_m, reflectivity R_m

The relation between the surface of the object and the surface of the base plate is: $(1 - \psi) : \psi$

The radiation, emitted by the kettle wall, hitting the object for the first time, i.e. nog being reflected by the object:

$$\varepsilon_k.C_s.(T_k/100)^4.\ \{1 + \psi.R_p.R_k + \psi^2.R_p^2.R_k^2 + \ldots + \ldots + \ldots\} =$$

$$\varepsilon_k.C_s.(T_k/100)^4/\ \{1 - \psi.R_p.R_k\}$$

The radiation, emitted by the base plate, hitting the object for the first time, i.e. not being reflected by the object:

$$\varepsilon_p.C_s.\ (T_p/100)^4.\ \{\psi.R_k + \psi^2.\ R_p.\ R_k^2 + \psi^3.R_p^2.\ R_k^3 + \ldots\} =$$

$$\psi.R_k.\varepsilon_p.C_s.(T_p/100)^4.\{1 - \psi.R_p.R_k\}$$

The radiation, emitted by the object, hitting the object itself for the first time, i.e. not being reflected by the object itself:

$$(1 - \psi)\ .\ \{\ R_k + \psi.R_k^2.R_p + \psi^2\ .\ R_k^3.R_p^2 + \ldots\ldots\ \} =$$

$$(1 - \psi)\ .\ R_k\ /\ \{1 - \psi.\ R_p.R_k\}$$

If this part is called F, and if the total amount of radiation hitting the object for the first time, without ever being reflected by the object is called Q_o, then:

$$Q_o = C_s.10^{-8}.\ \{\varepsilon_k.T_k^4 + \psi.\varepsilon_p.T_p^4.R_k + (1 - \psi).\varepsilon_m.T_m^4.R_k\}/$$
$$\{1 - \psi.R_p.R_k\}$$

The total amount of radiation hitting the object:

$$Q_o.\{1 + R_m.F + R_m^2.F^2 + \ldots\ldots\} = Q = Q_o/\{\ 1 - R_m.F\}$$

Substitution gives:

$$Q = C_s.10^{-8}.\{\varepsilon_k.T_k^4 + \psi.\varepsilon_p.T_p^4.R_k+\varepsilon_m.T_m^4.R_k.(1-\psi)\}/$$

$$\{1-\psi.R_p.R_k-R_m.R_k.(1-\psi)\}$$

Thus, the radiation reaching the radiation thermometer which has been pointed towards the object, will be equal to an energy flow Q_B which is proportional to

$$\varepsilon_m.C_s.(T_m/100)^4 + R_m.Q$$

Apart from the restrictions mentioned before, one can assume for non-transparent materials that $\varepsilon = A = 1 - R$; Therefore,

$$q_B \hat{=} \varepsilon_m.T_m^4 + (1-\varepsilon_m).\frac{\varepsilon_k.T_k^4+\psi.\varepsilon_p.T_p^4.(1-\varepsilon_k)+\varepsilon_m.T_m^4.(1-\varepsilon_k).(1-\psi)}{1-\psi.(1-\varepsilon_p).(1-\varepsilon_k)-(1-\psi).(1-\varepsilon_m).(1-\varepsilon_k)}$$

After transformation of this equation, we get

$$q_B \hat{=} \varepsilon_m.T_m^4+(1-\varepsilon_m).\frac{\varepsilon_k.T_k^4 + \psi.\varepsilon_p.T_p^4-\psi.\varepsilon_p.\varepsilon_k.T_p^4 + A.T_m^4}{A + B}$$

where: $A = \varepsilon_m - \psi.\varepsilon_m - \varepsilon_m.\varepsilon_k + \psi.\varepsilon_m.\varepsilon_k$

$B = \varepsilon_k + \psi.\varepsilon_p - \psi.\varepsilon_p.\varepsilon_k$

$$q_B \hat{=} \varepsilon_m.R_m^4 + (1-\varepsilon_m).\frac{\varepsilon_k.(T_k^4-T_p^4) + B.T_p^4 + A.T_m^4}{A + B} = T_B^4 \qquad \textbf{(I)}$$

T_B = temperature of radiation thermometer

Now the division in (I) can be adjusted:

$$T_m^4 + \frac{1}{A + B}.\{B.(T_p^4 - T_m^4) + \varepsilon_k.(T_k^4 - T_p^4)\}$$

Formula (I) now leads to:

$$T_B^{\,4} = T_m^{\,4} + \frac{1 - \varepsilon_m}{A + B}.\{B.(T_p^{\,4} - T_m^{\,4}) + \varepsilon_k.(T_k^{\,4} - T_p^{\,4})\}$$

$$A = (\varepsilon_m - \varepsilon_m.\varepsilon_k).(1-\psi)$$

Since the ratio between ψ and $1 - \psi$ is approximately 100 to 1, we can neglect A

Then we get:

$$\boxed{T_B^{\,4} = T_m^{\,4} + (1 - \varepsilon_m).\ \{(T_p^{\,4} - T_m^{\,4}) + \frac{\varepsilon_k}{B}.(T_k^{\,4} - T_p^{\,4})\}} \tag{II}$$

Since ψ is approximately equal to unity, we can write instead of

$$B = \varepsilon_k + \psi.\varepsilon_p - \psi.\varepsilon_p.\varepsilon_k$$

with fair accuracy $B = \varepsilon_k + \varepsilon_p.(1 - \varepsilon_k)$

Using (II) one would be able to calculate ε_m already; it would be possible to find the constant ε_k/B by measuring an object with known ε_m.
It is not always possible to measure T_m (temperature of the object), therefore we eliminate this factor by performing two different measurements.
T_m being kept constant and B varied (two different base plates will be used).

Plate 1: $$T_{B1}^{\,4} = T_m^{\,4}+(1-\varepsilon_m).\{(T_{p1}^{\,4}-T_m^{\,4})+\frac{\varepsilon_k}{B1}.(T_k^{\,4}-T_{p1}^{\,4})\} \tag{III}$$

Plate 2: $$T_{B2}^{\,4} = T_m^{\,4}+(1-\varepsilon_m).\{(T_{p2}^{\,4}-T_m^{\,4})+\frac{\varepsilon_k}{B2}.(T_k^{\,4}-T_{p2}^{\,4})\} \tag{IV}$$

Subtracting these two equations, we get:

$$T_{B1}^{\,4}-T_{B2}^{\,4} = (1-\varepsilon_m).\{(T_{p1}^{\,4}-T_{p2}^{\,4}) + (T_k^{\,4}-T_{p_{mean}}^{\,4}).\varepsilon_k.(\frac{1}{B1} - \frac{1}{B2})\}$$

$(\frac{1}{B1} - \frac{1}{B2})$ is a constant depending upon the positions of the kettle wall and the surface of the base plate; calling this constant k/ε_k, we get:

$$\boxed{T_{B1}^4 - T_{B2}^4 = (1-\varepsilon_m).\{(T_{p1}^4 - T_{p2}^4) + K.(T_k^4 - T_{p_{mean}}^4)\}} \qquad (V)$$

THE CONSTANT K

$$K = \varepsilon_k.\{\frac{1}{\varepsilon_k + \varepsilon_{p1}.(1-\varepsilon_k)} - \frac{1}{\varepsilon_k + \varepsilon_{p2}.(1-\varepsilon_k)}\}$$

where:

ε_k = emissivity of the Al-foil covered kettle wall
ε_{p1} = emissivity of the Al-foil covered half of the base plate
ε_{p2} = emissivity of the black-paint covered half of the base plate.

If we take an emissivity for Al-foil of about 0.04 and for black paint of about 0.97, we will find that K should be about 0.47. This value could change as a result of oxidation or contamination of the surfaces.
By doing a measurement on an object with a known emissivity, the constant K could be calculated very easily (Egn. V). In view of the above contamination and oxidation, regular measurements to calibrate K will be necessary.

MEASUREMENTS IN PRACTICE

If we look again at Egn (V), it is clear that several variables have to be measured in order to be able to calculate the emissivity.

T_{B1} = Radiation temperature while the Al covered plate is underneath the kettle
T_{B2} = Radiation temperature while the Black painted plate is underneath the kettle
T_{p1} = Al plate temperature
T_{p2} = Black plate temperature
T_k = Kettle wall temperature
K = Calibration factor for the equipment.

For an accurate tranformation from Egns. (III) and (IV) into (V), Tpl and T_{p2} must be almost equal.
In this measuring arrangement we achieve this by putting the plate (depending on the temperature difference) underneath the hot kettle.

Only if both plate temperatures are almost equal, the measurement will be started.
Because of the sensitivity of the radiation thermometer it is necessary for the accuracy of the measurement to have as big a difference between T_{B1} and T_{B2} as possible, which can be achieved by a big difference between the kettle and plate temperatures.

Measuring points

T_{B1} and T_{B2}	- 1	measuring point of the radiation thermometer
T_{p1}	- 2	measuring point, each 21 times the temperature difference between black and Al plate parts
T_{p2}	- 3	sensors at different positions on the black half of the plate
T_k	- 3	sensors at different positions on the kettle wall

Water temperature - one sensor (not necessary for calculation).
Temperature of the object - one sensor (only used if possible, not necessary for calculation).

One measuring cycle consists of 2 scans (once with the Al plate, once with the black plate underneath the kettle) and takes approximately 25 s.
Each measurement comprises 3 measuring cycles, so it takes 75 s.
In order to find the emissivity or the calibration factor K, the mean values are taken for the calculations only if no extreme values are obtained during a measurement.

Disadvantages of this measuring arrangement

a. It is difficult to maintain the temperatures of both plate halves equal.
b. Temperature differences in the two halves of the plate.
c. Very much mathematical work and calculations involved.
d. Limited range of the radiation thermometer (50°C).
e. Limited temperature of the kettle, because of the use of water as the heating medium.
f. Having to measure the calibration factor K repeatedly.
g. Changes of the temperature of the plates during a measurement.

IMPROVING THE METHOD OF MEASUREMENT

This improved method is based on the principle of comparing the known emissivity of a standard object with the desired emissivity of the object under test.
Apart from repeating the complete measurement, several scans have to made successively.

1. Al plate with the object to be tested.
   The reading of the radiation thermometer is called T_{B1M}
2. Black painted plate half with the object under test.
   The reading of the radiation thermometer is called T_{B2M}
3. Al plate and object with a known standard emissivity (gold).
   The reading of the radiation thermometer is called T_{B1S}
4. Black plate half and an object with a known standard emissivity (gold).
   The reading of the radiation thermometer is called T_{B2S}

From Egn. (V) we can write:

$$(T_{B1M}{}^4 - T_{B2M}{}^4) = (1-\varepsilon_m).\{(T_{p1}{}^4 - T_{p2}{}^4) + k.(T_k{}^4 - T_{p_{mean}}{}^4)\} \qquad \text{(VI)}$$

$$(T_{B1S}{}^4 - T_{B2S}{}^4) = (1-\varepsilon_s).\{(T_{p1}{}^4 - T_{p2}{}^4) + k.(T_k{}^4 - T_{p_{mean}}{}^4)\} \qquad \text{(VII)}$$

If during one measuring cycle the plate, kettle and object temperatures remain constant, division of (VI) and (VII) gives:

$$\frac{T_{B1M}{}^4 - T_{B2M}{}^4}{T_{B1S}{}^4 - T_{B2S}{}^4} = \frac{1 - \varepsilon_m}{1 - \varepsilon_s}$$

In order to be able to do all the calculations, there is only one measuring point that remains important, the radiation thermometer. For testing procedures, the plate and kettle temperatures will still have to be measured. However, this can be done before and after the real measurements. At least double the number of scans will be needed for this, but time can be saved (i.e. fewer temperature differences) because only need to measure one measuring point.
Now, several disadvantages listed in 8-2 no longer apply.

a. Difficulties to maintain the temperature of both plate halves equal (Egns (III) and (IV)).
c. The amount of mathematical work involved.

f. Repeatedly having to determine the calibration factor K.
g. Changes of the plate temperatures during measurement (least important).

CALIBRATING THE RADIATION THERMOMETER

The radiation thermometer (spectral response 8-14 μm) has been calibrated by means of a black body, specially constructed for this purpose (Fig. 2).

The black body consists of a copper container, into which a second copper container, painted black on the inside (ε paint = 0.97), has been fitted. The copper container has only a small hole on the top, so that it may be presumed that the heat radiation, leaving the container after having been reflected several times, is only a small proportion of the radiation entering the container, and the hole may be considered to be a good black body.

The temperature is measured at three points with thermocouples (copper-constantan) and controlled by an immersion heater in the surrounding water.

A small pump maintains a balanced temperature pattern inside the container.

INSTRUMENTS USED

During the measurements, the data are fed direct into the computer by the data logger and the measured values and required computed results are printed out the teletype (Fig. 4).

POSTSCRIPT

The development of the equipment described above has been started at end of 1972 and work continued with interruptions.

This study has been carried out with much assistance from J.B. Koenderink, staff of the department "Realization", and some voluntary workers from the HTS-school in Heerlen. The first prototype has been modified and improved several times.

Future, changes will be made mainly to make some handling operations automatic and to enlarge the spectral bandwidth.

NOMENCLATURE

Q = heat flux
T = temperature in degrees kelvin
ϵ = emissivity
R = reflectivity
ψ = relation between the real plate surface and the total bottom surface

SUBSCRIPTS

k = kettle
p = plate
m = object
b = radiation thermometer
1 = measurement in an arrangement with the Al foil covered plate half
2 = measurement in an arrangement with the black paint covered plate half

REFERENCES

1 - Ernst R.G. Eckert
Wärme- und Stoffaustausch.

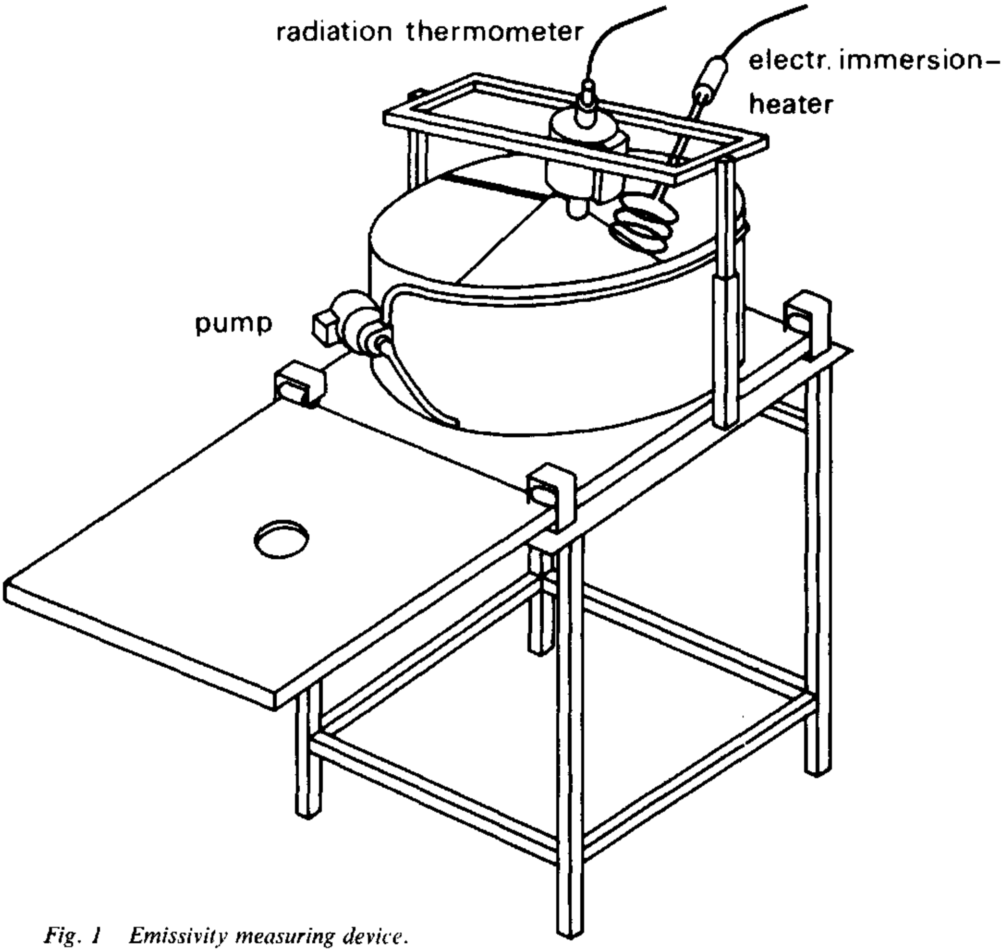

Fig. 1 Emissivity measuring device.

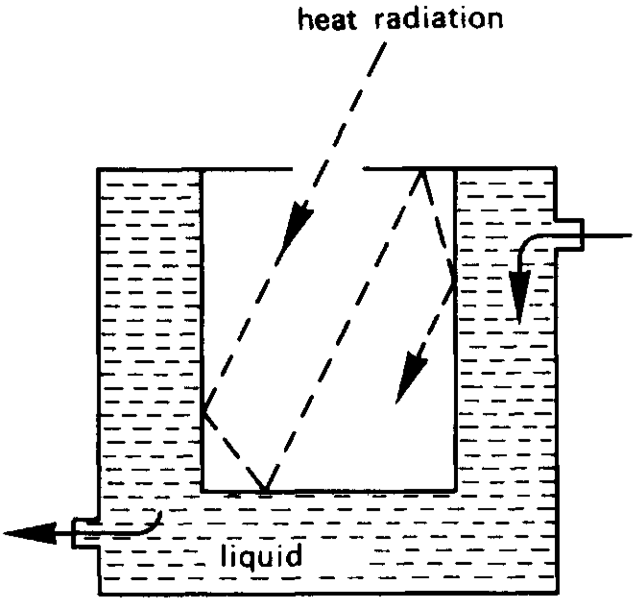

Fig. 2 Black body.

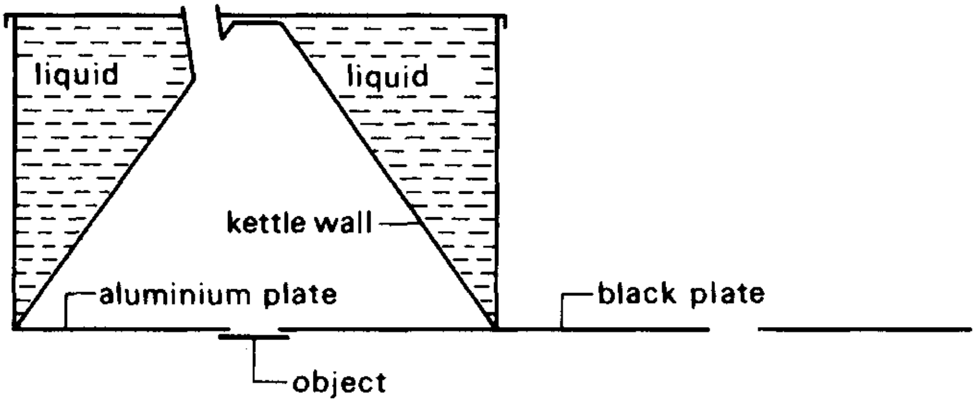

Fig. 3 Section of the emissivity measuring device.

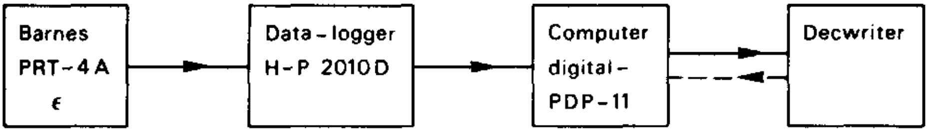

Fig. 4 Block-diagram.