DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

AND

FIRE OFFICES' COMMITTEE

JOINT FIRE RESEARCH ORGANIZATION

# FIRE RESEARCH NOTE

## NO. 531

# AN INSTRUMENT FOR MEASURING TOTAL HEAT FLUXES WITHIN FLAMES

by

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October, 1963.

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## 1. Introduction

The rate at which a fire burns in a compartment is determined by the feedback of heat from the flame and hot walls to the fuel bed. In order to measure the heat transfer to the fuel bed an instrument was required which could measure total heat fluxes up to 3-4 cal $cm^{-2}s^{-1}$ with an accuracy no greater than 5%, had a receiving angle of 180°, and was reasonably simple to operate. Descriptions of a number of instruments for measuring heat fluxes in this range and higher have been published, particularly by furnace and rocket engineers; Appendix I gives a broad classification and references.

The heat flow meter of Baulk and Thring(1) alone possessed all the desired characteristics and an instrument based largely on this was constructed and is described in this report. The principle of operation is that heat absorbed on the front face of a receiver is transferred to water flowing at a known rate through the receiver and the temperature rise of the water measured by thermocouples. The instrument of Baulk and Thring was used to measure heat flows up to at least 30 cal. $cm^{-2}s^{-1}$ and it was found that the water velocity through the receiver had to be high to avoid fluctuations in water flow due to steam formation.

When the performance of the present instrument was being investigated it was found that high water flows were required, not however to prevent steam formation, but to preserve the simple relation between heat flow and water flow and temperature rise. This is described further in Section 2.

## 2. Construction and operation

The receiver, (Fig. 1), is a circular copper disc 3.6 cm diam. blackened on the front face first with matt black paint, and then coated with soot in a town gas flame. Water flows in a spiral channel through the receiver and single thermojunctions of 36 s.w.g. copper-constantan wire, electrically insulated from the water by a thin coating of Araldite epoxy resin and paraffin wax, are inserted in the inlet and outlet tubes. The thermojunctions are spaced away from the tube walls by a small wire loop attached to the thermocouple wires near the junctions, but insulated from them. The internal diameter of the tube containing the junctions is 3 mm.

The receiver is enclosed, except for its front face, by an independent water-cooled jacket. The temperature of the jacket is virtually the same as the temperature of the receiver so that there is no heat transfer between them and the heat flux measured is that falling on the front face of the receiver, which has an acceptance angle of 180°.

The jacket and supporting arm were lagged with about 1½ cm of asbestos rope. The arm was not water-cooled since it was throught that this might cool the flame too much.

It was found necessary to insulate very well the joins between the thermocouple wires and the leads running up the arm centre, to prevent the joins heating up and generating a parasitic e.m.f. - even though these were copper to copper joins. With the joins protected by a sufficiently thick layer of asbestos insulation and extra cooling tubes added the parasitic e.m.f.'s were found to be very small. When the instrument measured fluxes larger than about 2 cal $cm^{-2}s^{-1}$ in a flame the outside of the lagging round the jacket became red hot, yet the zero reading obtained by withdrawing the instrument rapidly and pointing it at a cold surface was always less than 2 micro volts, corresponding to 0.07 cal $cm^{-2}s^{-1}$

Water flowed through the receiver from a constant head. During preliminary calibration experiments the instrument was exposed to a constant high intensity of radiation and the water flow was varied. It was found that the product of (water flow) and (temperature rise), which should be constant in an ideal instrument of this type, fell markedly at low water flows, but was constant for high flows. Two possible effects or their combination probably account for this behaviour:-

(1) When the flow was laminar the temperature registered by a thermocouple in the centre of the tube was appreciably lower than the mean water temperature.

(2) At low flow rates, and consequently high temperature rises, the heat loss may be significant.

The water flow was therefore maintained above 13 g/s, since above this value the product of (water flow) and (temperature rise) was almost constant.

Although it reduced the sensitivity the high water flow produced three desirable effects:-

(a) A low time constant (see Appendix 2). It has proved possible to make use of this rapid response in separating flame and wall radiation by a method in which the gaseous fuel supply was suddenly stopped and started.

(b) A constant water flow because there was no change in hydraulic resistance due to deposition on the tube wall of air or water vapour bubbles liberated at higher temperatures.

(c) A low heat loss. No correction was found necessary up to the highest heat-flux at which it could be accurately calibrated, 1.4 cal $cm^{-2}s^{-1}$ (see Section 3).

## 3. Calibration

In principle the instrument does not need calibration since the water temperature rise and the water flow can be measured directly. It was however clearly desirable to calibrate the instrument since for example the magnitude of the heat loss was unknown, and it was therefore calibrated against a Joint Fire Research Organization secondary standard thermopile (7) using as heat flux the radiation from a gas-fired furnace panel running at about 800°C.

The results of the calibrations are shown in Fig. 2, where the factor (water flow x thermocouple output) is plotted against incident radiation intensity, for water flows of 13 g/s and higher.

The results can be represented by the relation:-

$$I = kwe \qquad \text{..........} \quad (1)$$

where $I$ is the radiant intensity (cal $cm^{-2}s^{-1}$)
$k$ is a constant
$w$ is the water flow (g/s)
$e$ is the thermocouple output ($\mu V$)

Heat loss can hardly be important since points for similar intensities, but different water flows (and therefore different temperature rises) lie quite closely along one line. Further, there is good agreement between the theoretical and observed slope of the line. If no heat is lost:-

$$k = \frac{\sigma}{\pi r^2 a b} \qquad \text{..........} \quad (2)$$

where $\sigma$ = specific heat of water = $1$ cal $gm^{-1}$ $°C^{-1}$
$r$ = radius of receiving surface = $1.8$ cm
$a$ = absorptivity of receiving surface = $0.95$
$b$ = thermoelectric power of thermocouple = $42\ \mu V\ °C^{-1}$

Putting these values in equation (2) gives $\underline{k = 0.0024_7}$ cal $cm^{-2}g^{-1}\mu V^{-1}$

The value obtained from Fig. 2 is

$$\underline{k = 0.0025_0} \ \text{cal cm}^{-2}\text{g}^{-1}\mu\text{V}^{-1}$$

which agrees well with the calculated value.

If the heat flux is predominantly radiative $k = 0.0025$, but for a predominantly convective flux the absorptivity term is no longer required in equation (2) and a value of $k = 0.0024$ should be used. The use of a mean factor can lead to an error of no more than ± 2 per cent due to the proportions of radiation and convection being unknown.

## 4. Conclusions

(1) The total heat-flux meter is an instrument of rapid response and simple operation which can be used to measure total heat-fluxes up to 1.4 cal $cm^{-2}s^{-1}$ with an accuracy sufficient for most applications.

It has not been possible to calibrate the instrument at higher heat fluxes, since no suitable high-intensity radiation source is available at present, but the principle of operation makes it unlikely that the instrument can be substantially in error at heat fluxes of up to 3-4 cal $cm^{-2}s^{-1}$.

(2) It must always be remembered that what the instrument measures is the heat transfer to a cold surface of a particular shape and if in fact what is required is the heat transfer to a surface of different temperature and shape an allowance for these may be necessary.

## 5. Acknowledgment

The author would like to thank Mr. C. Shore for his help and advice with the design and for constructing the instrument.

## 6. References

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## APPENDIX 2

### Time constant of the total heat-flux meter

An approximate value for the time constant of the instrument can be calculated if the following assumptions are made:-

(1) The time constant is the same as that of the temperature rise in perfectly-stirred water flowing at the same rate as in the instrument through a copper container of the same weight as the receiver.

(2) There is no loss of heat

let $Q$ = constant rate of heat absorption of the container (cal/s)
$\theta$ = temperature rise ($^{\circ}C$)
$w$ = water flow (g/s)
$\sigma_w$ = specific heat of water (cal $g^{-1}\,{}^{\circ}C^{-1}$)
$M$ = water equivalent of copper container and contained water (g)

The differential equation is:

$$Q = w\,\sigma_w\,\theta + M\sigma_w \frac{d\theta}{dt} \qquad \text{..........} \quad (3)$$

and if $\theta = 0$ when $t = 0$

$$\theta = \frac{Q}{w\sigma_w}\left(1 - e^{\frac{-w\,t}{M}}\right) \qquad \text{..........} \quad (4)$$

The time constant is thus

$$\tau = \frac{M}{w} \text{ s}$$

For $M = 8.7$ g (Mass of copper 75 g, contained water 2g), $w = 15$ g/s, $\sigma = 1$ cal $g^{-1}\,{}^{\circ}C^{-1}$, $\tau = 0.6$ s

The time constant for $w = 15$ g/s was determined experimentally as 1.4 s, including the delay in response of the d.c. amplifier and pen recorder. This is of the same order as the theoretical value.

# APPENDIX I

## Classification of total heat-flow meters for the range 0 - 4 cal $cm^{-2}s^{-1}$

1. Steady-state instruments

1.1. Calorimetric instruments in which the heat flow is transferred to water flowing at a known rate, and the temperature rise is measured (1)

1.2. Plug-type instruments in which the heat is absorbed at one end of a plug of material of known thermal conductivity cooled at the other end, and the temperature drop along a well defined section is measured (2). The side heat loss is negligible, or a guard ring is used.

1.3. Thermometric instruments in which a body is allowed to attain thermal equilibrium and heat flow deduced from its temperature and heat balance (3, 4).

2. Instruments for intermittent use

2.1. Thermometric instruments in which the rate of rise in temperature of a body of known thermal mass is measured, by an attached thermocouple (5) or by its electrical resistance (6).

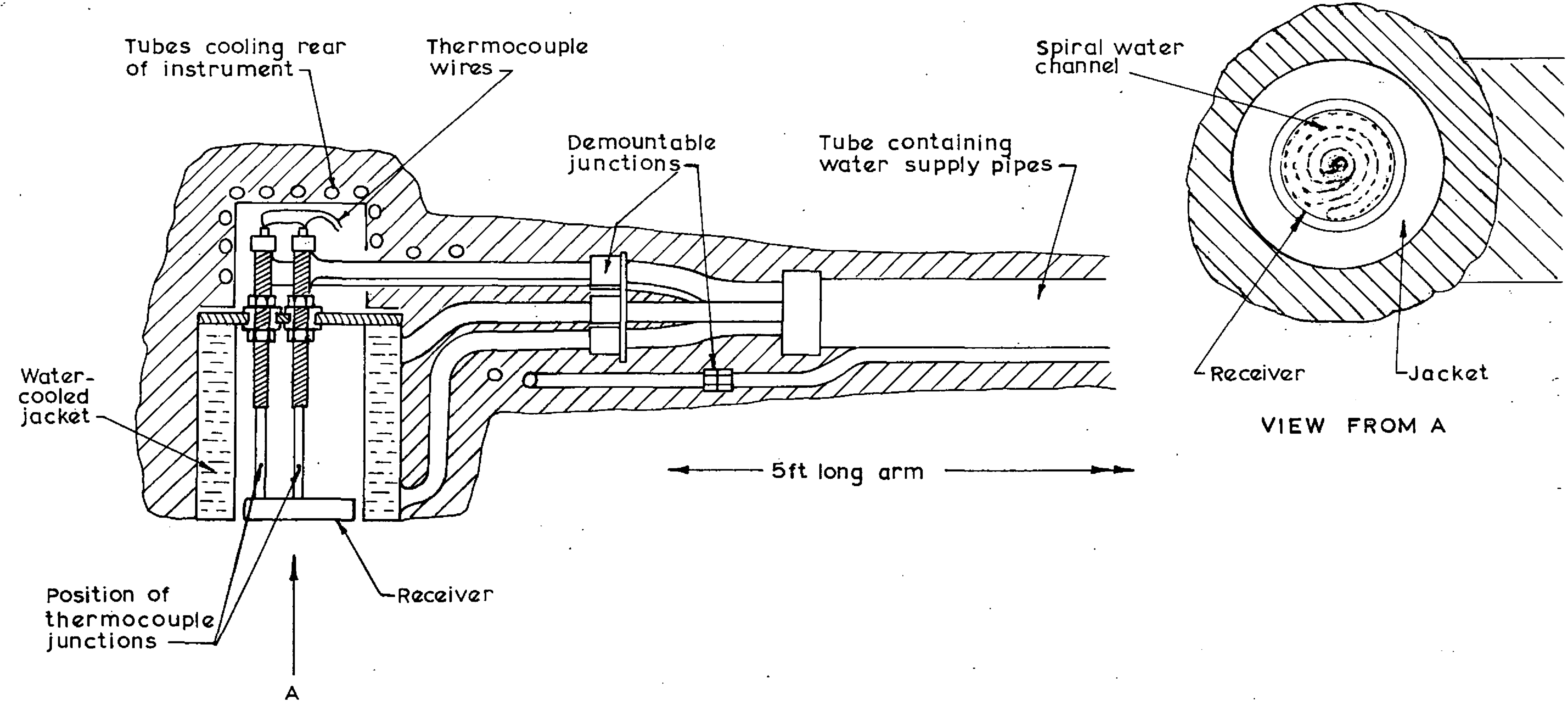

FIG.1. SCHEMATIC SECTION OF THE TOTAL HEAT-FLUX METER

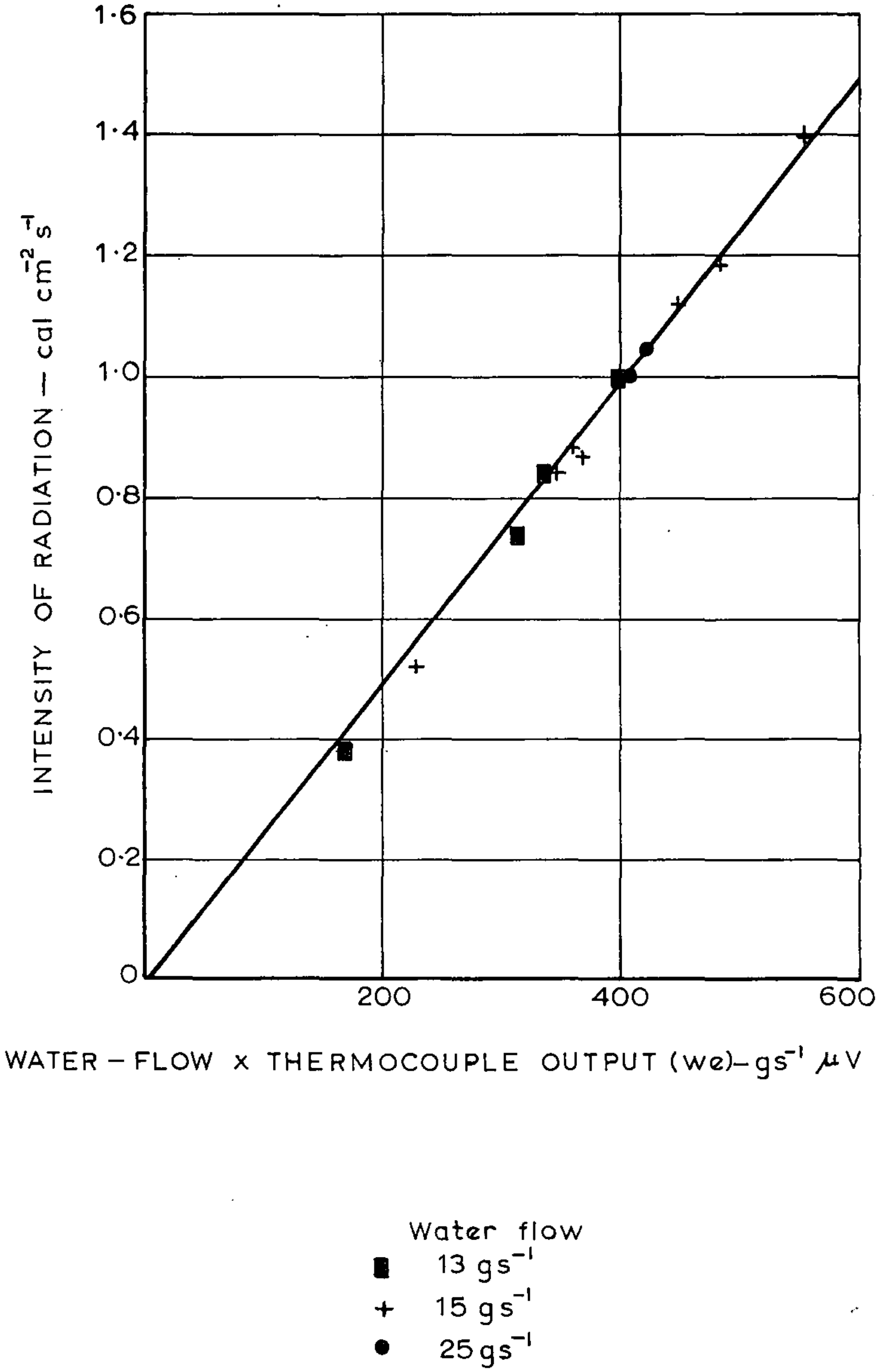

FIG. 2. CALIBRATION OF TOTAL HEAT-FLUX METER