TECHNICAL DEVELOPMENT

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A WIDE ANGLE HEAT FLUX METER

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Summary

A heat flux meter, which measures directly the flux of radiant energy and the flux of total energy integrated throughout a hemisphere, is described. The instrument is suitable for the measurement of the intensity of thermal energy in the range 200–20,000 BTU/h ft^2. It produces an e.m.f. directly proportional to intensity and has a very low time constant. The instrument is especially suitable for heat flux measurements in furnaces or high temperature systems. It may also be made to measure the radiant energy from the sun. Equations are derived to predict its performance, and the results are compared with experimental values.

Introduction

In recent years, new instruments have been designed to measure heat flux in various fields. Those used to measure radiative heat flux are called radiometer, while others used to measure total heat flux which includes radiative plus convective fluxes are called total heat flux meter. Houghton and Brewer[1] designed a radiometer suitable for measurements in the upper atmosphere. McGuire and Wraight[2] developed an instrument to measure energy level up to 100 cal/cm^2–s to determine the hazard to buildings exposed to fire. A total heat flux meter was developed by Cookson and Kilham[3] for use in the study of energy transfer from hydrogen-air flames. A radial disk type of total heat flux meter for carrying out heat transfer surveys in power station boilers was described by Northover and Hitchcock[4]. The instrument described here was developed for measuring radiant and convective contributions to heat transfer in a cylindrical test furnace for studying the heat flux distributions in the furnace[5].

Principle of the Heat Flux Meter

The heat flux meter described here consists of a hollow cylindrical body, one end of which is closed by a circular thin foil material thermoelectrically dissimilar from that of a body. Heat impinging the foil from a heat source, e.g., the furnace enclosure, flows radially outwards to the edge of the foil, then to the cylindrical body which forms a heat sink. The temperature difference is thus produced between the center of the foil and its rim. By attaching a wire to the foil center and one to the base of the body a net e.m.f. can be obtained from the hot junction formed by the wire and the disk, and the cold junction formed between the foil rim and the body. The e.m.f. so obtained is then a measure of the heat flux falling on the foil surface. For measurement of the radiative flux alone, a hemispherical window cap is mounted on top of the meter. When the cap is removed, the meter measures both radiative and convective fluxes.

Design and Construction

The design of the wide angle heat flux meter is as shown in Fig. 1 and 2. A constantan foil 0.001 in thick was soldered over the opening of the copper which acts as a heat sink. A 0.001 in diameter copper wire was welded to the center of the foil. Another copper wire was soldered to the base of the copper block. Thus a differential thermocouple was formed to measure the temperature rise at the center of the foil. This temperature rise can readily be related to the intensity of heat flux striking the foil. The constantan foil was blackened by spraying with flat black paint. The two copper lead wires were insulated by coating with insulating varnish to avoid any short circuit.

The copper block was mounted on an insulating material, asbestos cement sheet which sat on a brass pipe stem. The last $\frac{1}{2}$ inch of the block was threaded to permit the installation of a hemispherical window cap. Irtran–2 (Kodak–Eastman, N.Y.) was used as the hemispherical window to eliminate any convective heat transfer to the foil. This material transmits radiation from 2 μ up to 12 μ and is nearly immune to thermal shock. The radiative properties remain unchanged up to a temperature of 1500°F. The window was 20mm outside base diameter by 2mm thick. Details of the hemispherical window are shown in Fig. 2.

The radiometer was calibrated with a black body furnace of known heat flux, and later was checked against a heat flux meter which was available form Hy-cal Engineering, Calif. The meter model C–1301–A–15, serial No. 73777, was calibrated, certified, and traceable to the National Bureau Standard of U.S. The calibration factor of the radiometer was 5952.0 BTU/h ft^2–mV. The output was recorded by a 7100B strip chart recorder (Hewlett-Packard).

The radiometer without the hemispherical window is the total heat flux meter. Both convective and radiative fluxes would be absorbed on the foil, thus giving the total heat flux to the meter. A separate collar was made to fit on the meter in place of the hemispherical window to protect it from damage and to prevent it from absorbing heat from the exposed surface of the copper block.

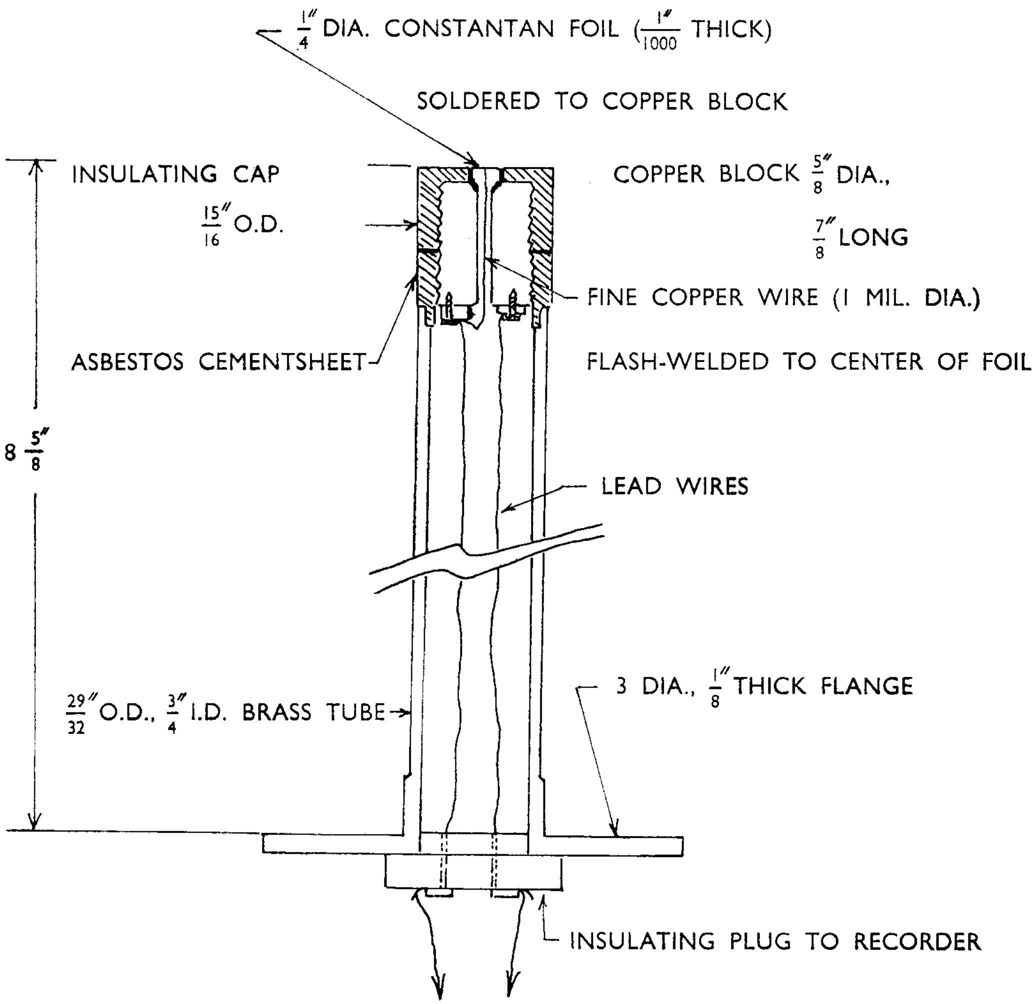

Fig. 1. Total heat flux meter (radiometer without the window)

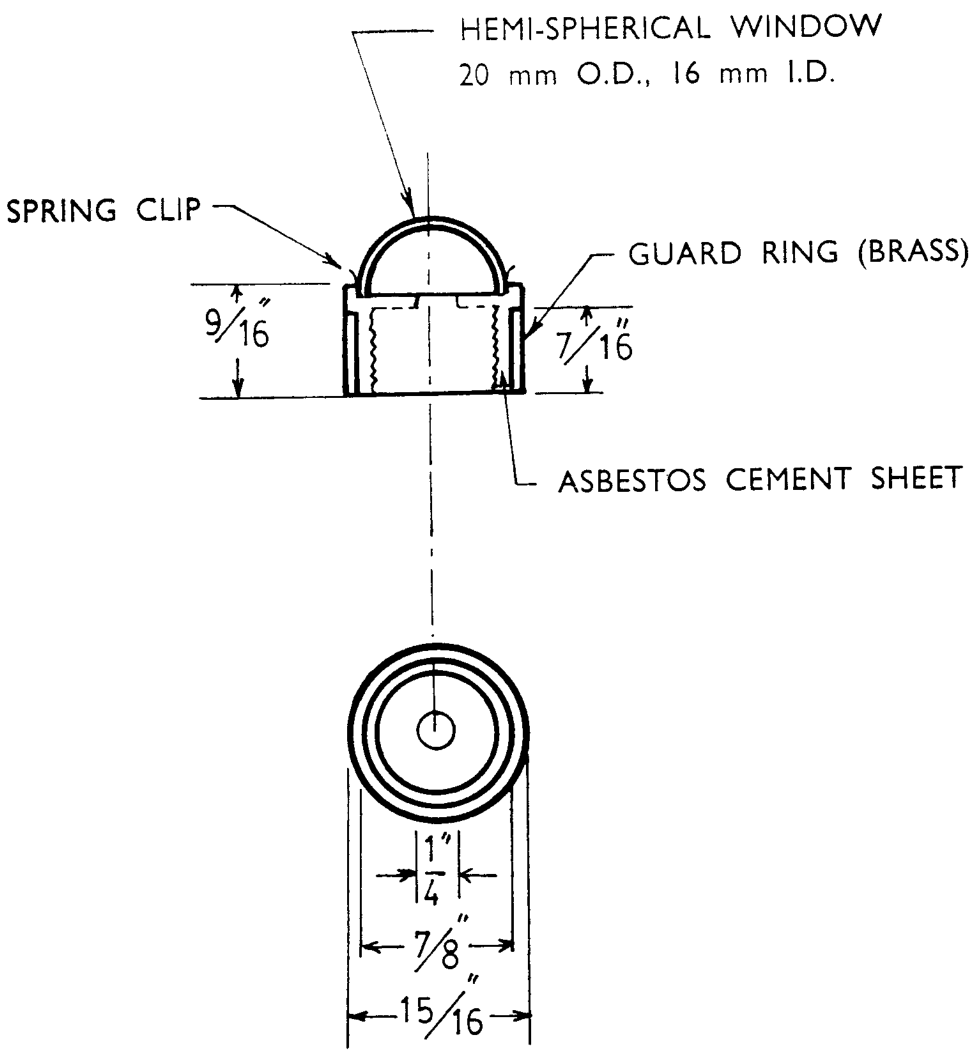

Fig. 2. Details of hemi-spherical window holder for radiometer

Fig. 1. shows the total heat flux meter. The total heat flux meter was calibrated in the same manner as the radiometer. The calibration factor of the meter was 4151.5 BTU/h ft^2–mV.

Theoretical Analysis of the Meter

Consider a thin circular foil of thickness W and radius R_o being attached around its circumference to a large heat sink maintained at a constant temperature T_o as shown in Fig. 3. Heat flux of Q_o impinging on the foil is absorbed. The energy balance is made for a thin ring of radius r and radial thickness δr with the following assumptions.

1. Heat losses from either side of the foil is negligible.
2. There is no temperature gradient across the foil thickness.

The energy equation is

$$C_p \frac{\rho}{k} \frac{\partial T}{\partial t} = \frac{Q_o}{Wk} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \qquad (1)$$

at steady state condition,

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = -\frac{Q_o}{Wk} \qquad (2)$$

The solution to equation (2) is

$$T - T_o = \frac{Q_o R_o^2}{4kW} \qquad (3)$$

where

T = temperature at the center of the foil, °F.
T_o = temperature of the sink, °F.
Q_o = heat flux, BTU/h ft^2.
W = thickness of the foil, ft.
R_o = radius of the foil, ft.
k = thermal conductivity of the foil, BTU/ft h °F.

The theoretical performance of the meter could be seen from equation (3). For the total heat flux meter the calibration factor was 4151.5 BTU/h ft^2–mV By substituting values of the right-hand side of equation (3), it was possible to calculate $(T\text{-}T_o)$.

with

Q_o = 4151.5 BTU/h ft^2
W = 0.001/12 ft.
R_o = 0.25/(2×12) ft.
k = 14 BTU/ft h °F for constantan,

therefore

$T - T_o$ = 96.53°F

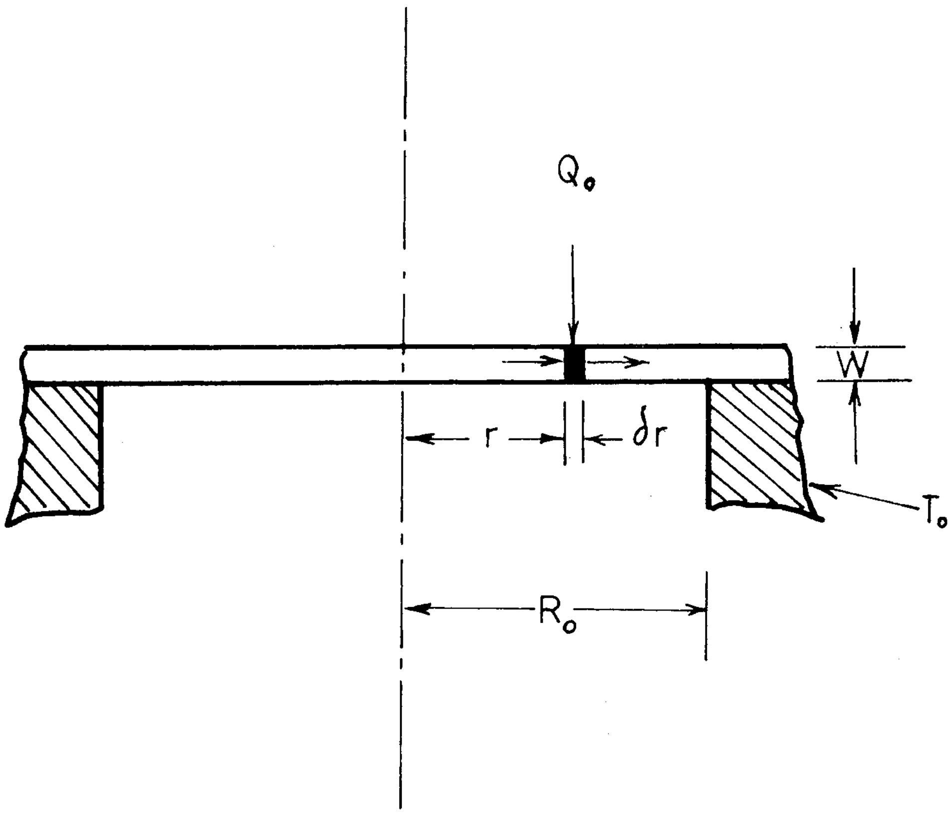

Fig. 3.

The approximate conversion factor for copper-constantan is 43°F/mV for the temperature range used. This indicated that the sensitivity of the meter from the theoretical analysis was twice better than the actual performance of the meter. The causes for this difference were numerous; for example, in the assumptions made in deriving the equation, the black paint applied on the foil surface would make the foil thickness much larger than 0.001 in, and there are defects in manufacturing technique of such a small device. However, the meter was used with the actual calibration factor, and it was quite successful for use in a cylindrical furnace to measure the total flux and radiant flux separately, so that convection could be obtained by difference.

From the consideration of equation (3), it was clear that the sensitivity of the meter might be increased so that it could be used to measure heat fluxes from lower heat flux sources such as from the sun. This might be achieved by decreasing the thickness of the foil and also by increasing the foil diameter. The constantan foil as thin as 0.0001 in can be obtained commercially. If this thickness is used, the sentivity would be expected to be 10 times better.

Conclusions

The wide angle heat flux meter described above would appear to be a useful device with which to measure energy transfer from a high flux source with a hemispherical view. It can also be made to measure heat fluxes from lower heat flux sources such as from the sun.

The meter has been successfully used to measure heat flux distributions along a cylindrical furnace wall. The design and construction was simple and it could be easily made.

References

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บทคัดย่อ

ได้บรรยายถึงเครื่องมือวัดพลังงานความร้อนซึ่งสามารถใช้วัดพลังงานความร้อนจากการแผ่รังสีและปริมาณความร้อนทั้งหมดที่ตกลงมาเป็นมุม 180° เครื่องมือนี้ใช้ได้ดีในการวัดพลังงานความร้อนที่มีความเข้มระหว่าง 200–20,000 บีทียู/ชม. ตร.ฟุต โดยจะอ่านออกมาเป็นค่า e.m.f. ซึ่งเป็นปฏิภาคโดยตรงกับค่าความเข้มของพลังงานความร้อนและเป็นเครื่องมือที่มีความไวสูง เหมาะสมที่จะใช้ในการวัดพลังงานความร้อนในเตาที่มีอุณหภูมิสูง นอกจากนี้อาจจะนำมาดัดแปลงเพื่อใช้ในการวัดพลังงานจากดวงอาทิตย์ก็ได้

ได้แสดงสมการที่อธิบายถึงการทำงานของเครื่องมือและเปรียบเทียบผลกับค่าที่ได้จากการทดลอง