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Design and Fabrication of Plate Thermometer for the Measurement of Incident Radiation Heat Flux on a Surface

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Abstract: ***This paper deals with the heat transfer mechanisms in a furnace, and explains the use of a plate thermometer to measure the incident radiation heat flux at a point, replacing conventional heat flux meters.***

Keywords: Heat transfer, radiation, Heat flux meters, conduction correlation factor, plate thermometer

1. Introduction

Conventional heat flux meters are extremely fragile and come at an exorbitantly high price which limits their usage for measuring the heat flux inside a furnace. The use of a plate thermometer was suggested by Wickstrom, to replace these HFMs by making a low cost device, which could be used in the calculation of radiative heat flux inside a furnace[1]. The importance of finding the heat flux, lies in the fact that it could be used to predict the amount of heat flux through a combustible substance, kept inside a room and help to prevent the occurrence of an accident. This would require the use of a fire safety system working with the plate thermometer. This is the motivation for this paper.

2. Literature Survey

The plate thermometer has the following design:

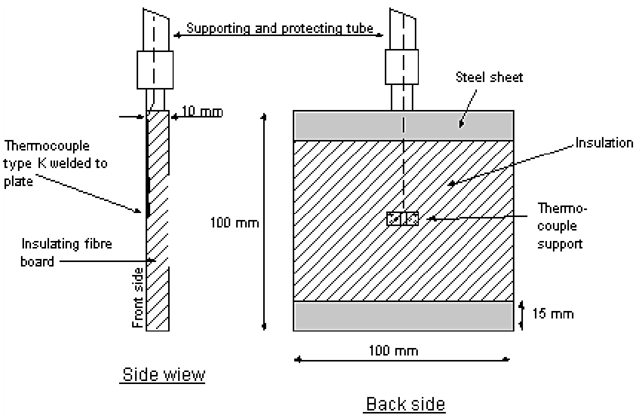

Figure 1 Design of the plate thermometer

Inconel sheets are preferred for making a plate thermometer due to their high thermal conductivity and high percentage of nickel which makes it suitable for use at high temperatures. But inconel is not easily available in India, and since experiments had already been performed with inconel , we decided to use stainless steel (SS304) as the material for the plate because it was the closest to incolnel when it came to the thermal properties. Since it has a lesser thermal resistance than inconel, we decided to increase the thickness by 3mm.

The total heat flux incident on the plate thermometer is the sum of the convective and radiative heat fluxes. By energy balance, thus total flux can be equated to the storage and conductive heat losses in the plate thermometer.

$$\dot{q}_{total} = \dot{q}_{radiation} + \dot{q}_{convection} = \dot{q}_{stored} + \dot{q}_{conduction} \quad (1)$$

Where $\dot{q}_{total}$ = total heat flux reaching the plate thermometer from the flame in the furnace.

$\dot{q}_{radiation}$ =radiation component of the incident heat flux

$\dot{q}_{convection}$ =convection component of the incident heat flux

$\dot{q}_{stored}$ =heat flux stored by the material of the plate thermometer (PT).

$\dot{q}_{conduction}$ =heat flux conducted across the surface of PT.

Also, the radiation heat flux can be calculated by the following equation:

[illegible]

(2)

Here, the two Stephen Boltzmann constants are known and we measure the surface temperature using the thermocouple and infra-red camera.

The convection part is given as:

$$\dot{q}_{conv} = h(T_{film} - T_s) \quad (3)$$

For 'h', we refer to standard material values using Nusselt's number. For the stream temperature we again have a thermocouple just at the surface to measure that. The value of h (convective heat transfer coefficient) can be obtained from the nusselt correlation using only the surface temperature and the temperature of the ambient air [3].

The conductive flux can be easily calculated using Newton's law of conduction and the back side temperature. Lastly, for the storage heat losses, we need a material constant. This would be obtained by calibrating our instrument against a standard reading (preferably a cone calorimeter) and thus getting that value by comparing the incident flux readings.

$$\dot{q}_{cond} = K_{cond}(T_S - T_{fire}) \quad (4)$$

$$\dot{q}_{sto} = \Lambda(\partial T_S/\partial t) \quad (5)$$

Where Λ is the heat capacity of the plate of the PT.

Once we get that constant, we can work backwards, put that constant in the equation and use our instrument to measure incident heat fluxes in many robust conditions.

[illegible]

(6)

3. Calibration of Thermocouples

3.1 Initial Experiment

The thermocouples that were used were not steel braided but normal K-type thermocouples.

First the weld bead was made on the thermocouple, then the bead of the thermocouple was joined to the centre of the plate thermometer using an epoxy adhesive which doesn't degrade at high temperatures. Some testing was done to check the accuracy of the thermocouple, by using an infrared thermometer, and 2 multimeters. For this testing, 2 other thermocouples were joined to the plate at small distances from the centre. The readings from the two thermocouples and the one at the centre differed slightly, as can be seen from the readings. Then the gap in the plate thermometer was completely filled using pyrofoam.

For the first experiment, the plate thermometer was hanged vertically on one wall using the thermocouple, such that the steel sheet directly faced the flame. The flame was generated using an LPG cylinder and was put about 40-50cm from the plate thermometer. An infrared camera was used to take thermal images of the setup during the experiment, and a heat flux sensor provided the exact values of the incident heat flux as it was positioned very near to it.

Figure 2 Experimental setup

Figure 3 Experiment being performed with a small flame

3.2 Outcome of First Experiment

In the first experiment we found significant deviation between the values of the heat flux measured by the heat flux meter and those obtained from the plate thermometer after doing the required calculations. Figure shown below represents the deviations between the values.

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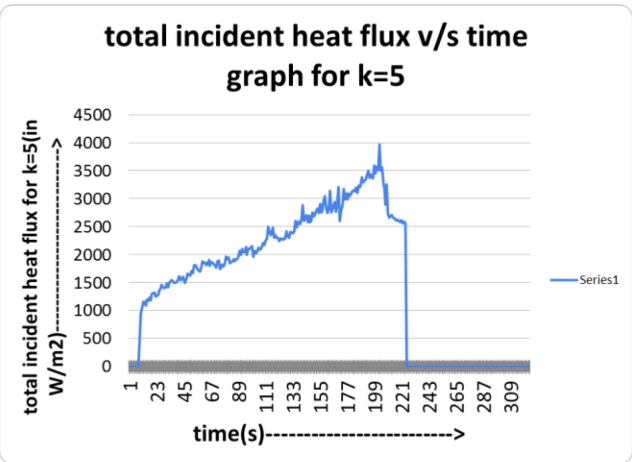

Figure 4 Variation of heat flux with time in the first experiment

The above graph represents the calculated value of incident heat flux using the plate thermometer.

The next graph shows the radiation heat flux measured by the heat flux meter.

As it can be clearly seen, the measured and calculated values greatly differ and this anomaly is due to the fact that the assumption of taking the temperature of the front side of the plate to be equal to the temperature shown by PT was wrong.

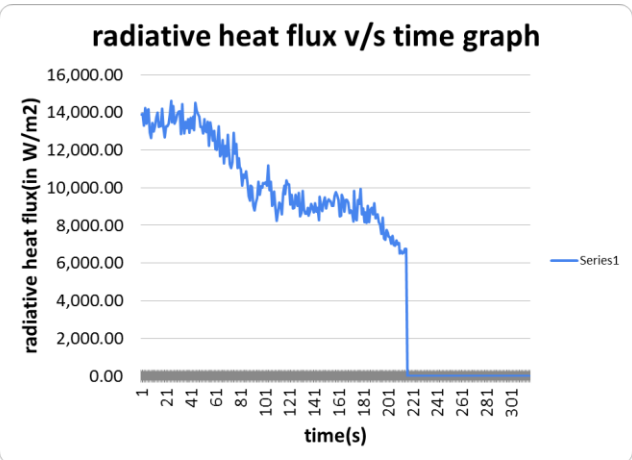

Figure 5 Variation of radiative heat flux with time in the first experiment

3.3 Second Experiment after Modifications

Improvement in the design:

1) This time the front side of the plate which is exposed to direct heat from the flames, was coated with a layer of black paint to improve its ability to absorb and emit more heat with the surroundings.
2) Steel braided thermocouples were used, since these are more resistant to high temperatures and the voltages do not get affected by the heat from the flames.
3) Instead of the epoxy adhesive used in the first experiment, a high temperature epoxy adhesive was used which could withstand much higher temperatures (up to 1000K) than the previous one.

3.4 Experimental setup

We performed 3 more experiments by putting the plate thermometer in 3 different configurations.

Remark: In all these 3 cases, a thermocouple was kept very close to the front surface to measure the surface temperature and the following observations were recorded:

1) The surface temperature and the temperature of the PT (thermocouple on the backside of the plate) were not the same and had a difference of even 60-70K at some instants of time. This is contrary to what had been assumed in the research paper that we used as a reference for this project.
2) Since in these cases, the plate thermometer was kept very close to the flame, sudden fluctuations occured in the values of recorded heat flux as the flame sometimes touched the front plate. This was important for us to measure because, this represented a **transient** case of heating and plate thermometers are usually not very accurate in the transient part.
   So in order to calibrate the plate thermometer in the transient region also, these experiments were done very close to the flame [10].

Case 1:
The first experiment was performed with the same setup as done in the first experiment, but the readings still deviated significantly from the values obtained using the heat flux meter.

Case 2:
In this case, the plate thermometer was kept directly above the flame in such a way that the tip of the flame sometimes touched the surface of the plate thermometer.

Figure 6 Orientation of the Plate Thermometer in case 2

The results of the experiment are shown in figure below.

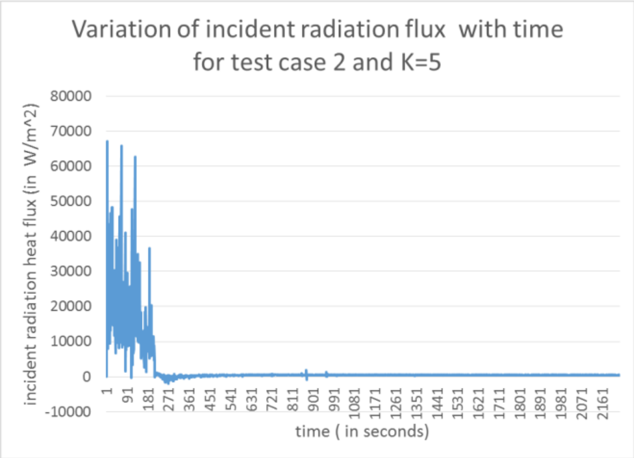

Figure 7 Variation of heat flux in case 2

Case 3:
In this case the plate thermometer was kept to one side of the flame at about the middle of the peak flame height. Results are shown in the figure and were obtained for different values of K (conduction correlation factor). Here only one of them has been shown for K=5W/m^2K

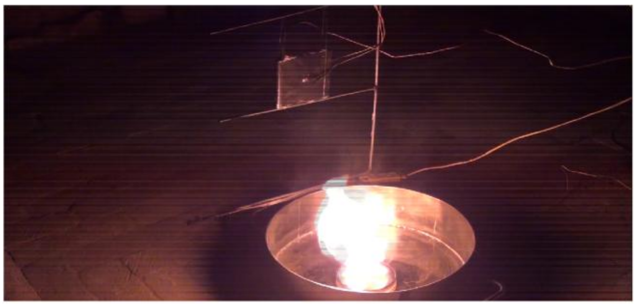

Figure 8 Orientation of Plate thermometer in case 3

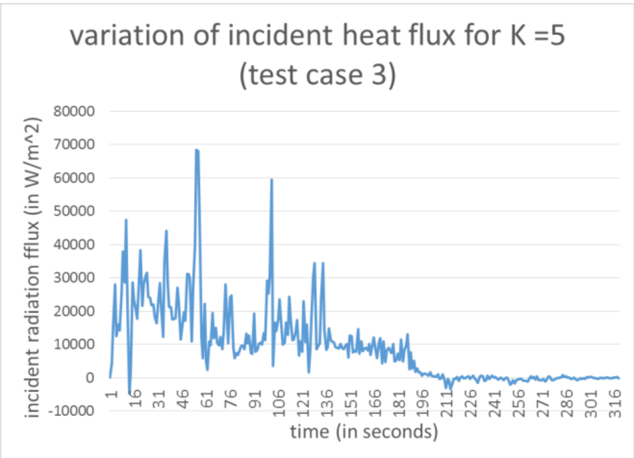

Figure 9 Variation of heat flux in case 3

In the above graphs we find that the values of radiation heat flux calculated from the plate thermometer match closely to those obtained from the heat flux meter in all configurations.

Remark: In case 3 the heat flux goes down to zero at a slower rate than case 2 because, when the PT is kept at the top of the flame, as the intensity of the flame reduces, the heat flux will smoothen out as the flame would not be touching the PT and would be at a considerable distance away from it.

But in case 3, the PT is kept to one side of the flame and the flame kept on touching it even when it had reduced in intensity, thus the frequent spikes in measured values of heat flux.

3.5 Final Experiment

In the final experiment, instead of using just one thermocouple at the centre of the plate thermometer, we used 4 extra thermocouples arranged at the vertices of a square around the central thermocouple.

This was done in order to verify the assumption that the whole surface of the plate thermometer has nearly the same temperature.

From the observations, the thermocouples showed a deviation of only about 3-4K which could be considered as negligible, and therefore the whole plate could be assumed to have the same temperature on the side directly facing the flames.

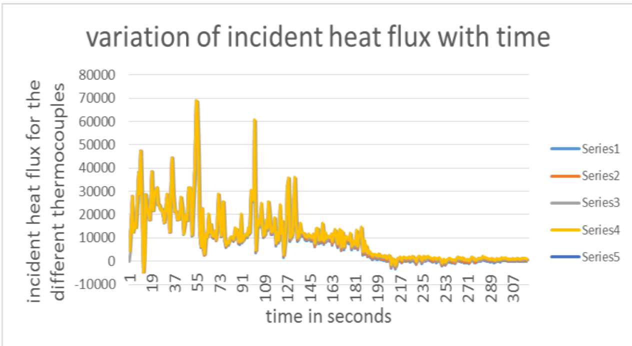

Figure 10 Results of the final experiment with 4 thermocouples at the corners and 1 in the centre

Remark:

In all the above experiments, we studied the dependence of the calculated heat flux values on the conduction correlation factor K.

Assuming values of K as 5,10,15,20,25 W/m^2 K, we found that the closest fit to the measured values of heat flux occured for K=5 W/m^2K.

This is why in order to keep the report concise, all the graphs of calculated heat fluxes using the plate thermometer, shown in this report are for K=5 W/m^2K.

Method of Calculations

We obtained voltage difference values from the thermocouples and the heat flux sensor, and using their calibration constants, the corresponding temperatures were calculated.

From these temperatures, the corresponding values of heat flux were calculated as shown in the theory.

3.6 Other Considerations in the Experiments

1) Significantly high conduction heat flux value across the thickness of the plate, even though an insulation of pyrofoam was present to make the rear face of the plate insulated.

For finding out the reason for this error, we once again performed the experiments, but this time:

i) A thermocouple was connected to the front surface of the plate thermometer to record its temperature and,
ii) The pyrofoam insulation which was previously just packed with the plate thermometer was properly attached to the rear surface of the plate using an adhesive.

We thought the main reason for the difference in temperatures between the front and rear surfaces were due to improper insulation at the rear surface which resulted in a temperature gradient along the thickness.

Also, due to the thermocouple coming out from the rear surface of the plate, a small gap was present between the insulation and the rear surface of the plate.

The following results were obtained from the experiments:

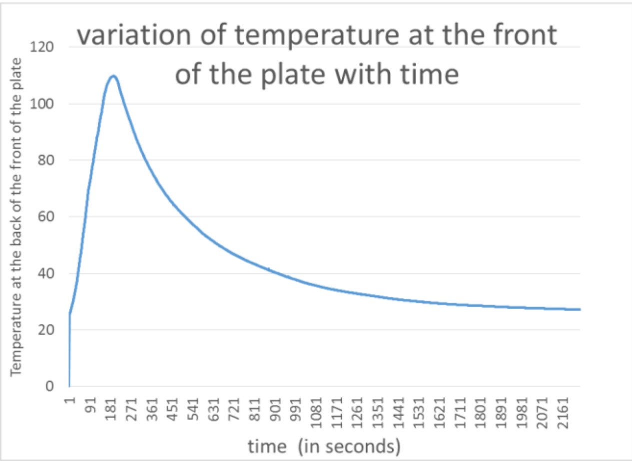

Figure 11 Temperature variation at the front surface

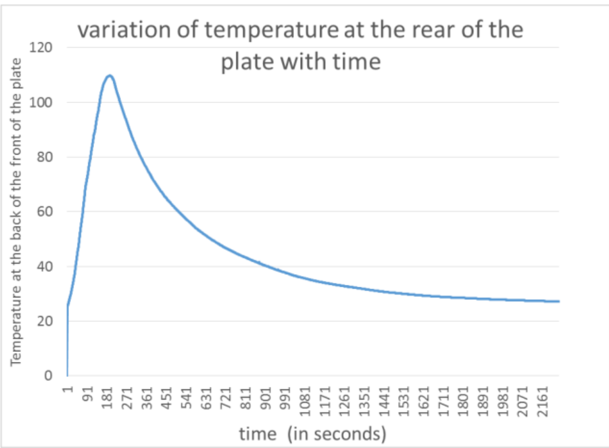

Figure 12 Temperature variation at the rear surface

The above graph shows the variation of temperature of the front surface of the plate with time.

As can be seen from the graphs above the temperature difference between the 2 surfaces was less than .01 degree Celsius at any instant of time and hence the conduction heat flux was very small.

But still, due to the conduction losses in the 2-D plane, i.e. from the center of the plate to its edges was not negligible, it was approximated using a conduction correlation factor K, whose value was experimentally found out to be 20 W/m^2/K, by comparing the incident heat flux measured by the PT to that measured by the heat flux meter [4].

Since the value of conduction heat losses was closely approximated by the use of conduction correlation factor K, we got very good matching of heat flux between the plate thermometer and the heat flux meter, as shown below.

<u>Heat balance equations</u>: q represents the heat flux

$$q_{total} = q_{radiation} + q_{convection} \quad (7)$$

This is the total heat received by the plate from the surroundings.

[illegible] (8)

⇨ Also, for the heat flux on the plate, it is transmitted by 2 mechanisms, some part is stored and the rest of it is conducted (which should be negligible)

⇨ $$q_{total} = q_{stored} + q_{conduction} \quad (9)$$

The values of Qtotal should be same from both the above equations for heat balance to be verified.

The following are some of the values found at different time steps:
Q total has been calculated by the sum of heats from radiation and convection.
Q incident is found from the formula below:

[illegible]

(10)

2) Literature review of the Nusselt number relations used for calculating the convective heat transfer coefficient, h:

The relation used for the calculation of heat transfer coefficient were as follows:

$$Nu = C * Ra^m \quad (11)$$

Where Nu is the nusselt number and Ra is the Rayleigh number and C and m are constants which are determined for the given type of flow and geometry.

The flow inside the furnace could be safely assumed to as that in free convection due to the absence of any flow generating unit like a fan,etc.

Also, for a hot surface up or a cold surface down type of horizontal plate, exposed to natural convection, 10^5<Ra<10^7 and hence C=.54, m=1/4 (These values have been taken from the reference [1] mentioned later).

Now, Rayleigh number is product of grashof number and prandtl number (which has value of .7 for air) and

Gr= $\beta * g * (T_s - T_\infty) * L^3/v^2$ (12)

Also, $Nu = hL/K_g$ (13)

Where Kg can be assumed as the conductivity of the gas i.e. air in this case.

The properties of air , Kg and β are determined at the film temperature i.e. average of Ts and ambient temperature.

Kg= $13.75 * 10^{-5} T_f^{0.92}$ (14)

$v = 1.13 * 10^{-9} T_f^{5/3}$ (15)

Using the above relations, we get the required relation for the convective heat transfer coefficient as follows [7]:

$$h = 4.0 * \left(\left(\frac{T_s - T_\infty}{L} \right)^{.25} \right) * (T_s + T_\infty)^{-.16} \quad (16)$$

Using the above relation, we found the value of h at every time step, as we knew the ambient temperature and the surface temperature of the plate thermometer

4. Discussions and Conclusions

It is shown in this report that incident radiant heat flux can be obtained indirectly from plate thermometer measurements. The PT was, however, designed for monitoring temperature in fire resistance furnaces and not for measuring incident radiant heat flux in air at ambient temperature as discussed here. Corrections are therefore needed as is outlined in this paper to compensate for conduction and convective errors.

Conduction losses could be substantially reduced by avoiding direct metal contact at the edges between the front and back sides of the PT and by using thicker and more effective insulation pads. The inertia could also be considerably reduced by using thinner steel plates and thereby getting much faster responses to thermal changes. Such modifications of the PT design for use in ambient air are possible. The PT does not normally need to be as robust when used in ambient air as when used in fire resistance furnaces.

5. Other Recommendations

The above report explains the design and construction of a plate thermometer, and the way it is calibrated against a standard (a heat flux sensor in this case). In order to calibrate it more accurately, we could change the values of the conduction correlation factor, and perform iterations until we get the closest fit with the measured values or we could also change the material or thickness of the plates used to manufacture it.

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