AN INVESTIGATION OF THE ABILITY OF A THIN PLATE HEAT FLUX DEVICE TO DETERMINE THE INCIDENT HEAT FLUXES DURING ENCLOSURE FIRES

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(Received 19 Jan 2001; Accepted 20 March 2001)

ABSTRACT

The incident heat flux (including its convective & radiative components) is considered to be the most accurate and direct quantifier of the fire induced thermal impact on a compartment boundary element. From the examination of current literature, 'The Destructive Potential of a Fire' has been proposed as the most satisfactory approximation of the term 'Fire Severity'. Based on the aforementioned premise a Thin Plate Heat Flux Measurement Device (TPD) has been developed which allows the accurate and economic measurement of the incident heat flux. This paper describes the further development of the TPDs for the determination of fire severity for enclosure and furnace fires. Two one-third scale ISO fire test enclosures and an ISO room compartment were employed to assess the capabilities of this device. Tests were conducted regarding the performance TPDs in various conditions including lining tests. From the resulting analyses, improvements in the calibration techniques resulted and the ability of the devices to perform under varying conditions was verified. Consequently the information related to this project will have the potential to further contribute to the enhancement of the existing knowledge of compartment fires and allow the accurate measurement of fire severity.

1. INTRODUCTION

It is clear that a considerable amount of experimental work has been undertaken with respect to compartment fire tests over the last 40 years particularly regarding the determination of a better understanding of the factors and variables influencing the growth and development of real world compartment fires.

Recently, during some research into 'Fire Severity' it became apparent that, instead of a definition for the above term and a single agreed method for its quantification, there were several definitions being used for describing fire severity and various methods employed for its quantification [1]. Moreover, numerous researchers have stated that fire severity is an ill-defined term and thus difficult to quantify adequately.

This was highlighted by Devaney [2], who stated that whilst the term 'Fire Severity' would seem to be a well used term in Fire Safety Engineering Research, its meaning has changed, depending on the area a particular researcher may be work in. Moreover the terms relating to 'Fire Severity, such as Equivalent Fire Resistance (sometimes called equivalent fire severity or effective fire resistance) and Fire Resistance' have been confused and misused. In concurrence with this Shields [3] stated that "there is a need for unification of the terminology currently in use". Nonetheless, it would appear that the term, 'the destructive potential of a compartment fire' used to describe fire severity may in the first instance be considered as a reasonably satisfactory definition.

However, the generation of a universally agreed method of quantifying 'Fire Severity' will require a substantial research program. In relation to this, factors known to influence the severity of a compartment fire include: fire load density, distribution of fire load, compartment scale, compartment geometry, ventilation opening and position, thermal properties of the compartment boundaries, gas temperatures, incident heat flux and duration of burning. These and other terms, have been used by various researchers [e.g. 4-8] to give expression to fire severity. However an agreed method of measurement and assimilation of these variables, to predict the destructive potential of a fire within a real compartment or building, has to date remained unavailable.

In this regard shortcomings of the various methods and instrumentation employed in the measuring of fire severity parameters have been discussed in Lennon & Silcock [1]. For example the limitations of the equal areas under the temperature/time curve as a measure and indeed the use of gas temperature as a quantifier of fire severity have been emphasised. The potential advantages of the use of the incident heat flux as a quantifier or definition of fire severity have been highlighted by Lennon & Silcock [1] and Silcock and Shields [9].

This paper discusses endeavors to analyse and understand the implications of the proposed quantification method of fire severity, i.e. the measurement of the incident heat flux via the use of the TPDs based on a concept reported by the Vatell Corporation [10] and outlined in Lennon & Silcock [1]. In the following paragraphs a discussion of the key areas of investigation and the issues encountered during the early stages of the development of the TPD, including its calibration and use in the partitioning of incident heat flux into its radiative q''_{rad} and convective q''_{con} components is given.

In order to assess the flexibility and robustness of the TPD, a series of proving experiments were conducted at reduced and full scale to determine the magnitude of fire induced thermal fluxes.

2. METHODOLOGY

2.1 Instrumentation

A TPD consists of 14 mm diameter stainless steel discs 0.15 mm thick with a Type K thermocouple cable welded to the back face of each disc (See Fig. 1). The device consists of a pair of thin disc/thermocouple assemblies one coated with a high emissivity paint (0.96) and the other with a low emissivity stainless steel foil (0.1). Emissivity was determined from calibration via an infrared thermometer IT-330, a hot plate and a type K surface thermcouple. Each TPD was calibrated for a range of radiative incident heat fluxes of from 0.5 to 45 kWm^{-2} approximately using the radiant field of a Cone calorimeter furnace heater. Subsequently for maximum accuracy calibration graphs were produced for low, medium and high flux ranges for each TPD.

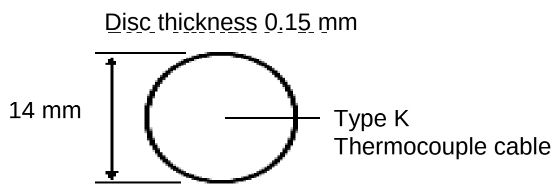

Fig. 1: Thin plate device design

The Total Flux Gardon gauges were cooled by a portable water circulatory system. The calibrated Aspirated Thermocouples employed consisted of a stainless steel tube of a 4.6 mm internal diameter with a 1.5 mm Type K thermocouple inserted inside with the tip 12 mm from the end of the tube. Air suction for these instruments was provided by a pump providing suction of 4.9 litres per minute per aspirated thermocouple. All data was recorded via a data logger recording at 10-second intervals.

2.2 Test Compartments

The programme of research, designed to interrogate the TPD methodology and its accuracy, employed two reduced scale test cells and a large-scale ISO test room compartment labeled A, B and C respectively. These preliminary tests are now described in some detail including the instrumentation used in the following sub paragraphs.

2.2.1 Test Compartment A

This test compartment was an approximate one-third scale replica of the ISO room with internal dimensions 800*1200*800 mm high with a 267*666.7 mm door opening in one sidewall. The walls and ceiling were insulated with Fibrefax duraboard and externally lined with plywood to give structural support. The floor was of a masonry tile construction.

For the calibration tests, the instrumentation was positioned as shown in Fig. 2. For comparison purposes a water-cooled Total Flux Gardon Gauge was also employed adjacent to each TPD. The fuel used was Industrial Methylated spirits with, in some cases, a small amount of diesel oil added to the total fuel volume and was contained in a fuel tray measured 200*200*50 mm deep. All data was again recorded using a data logger set to record at 10-second intervals. For the calibration tests Type K thermocouples and aspirated thermocouples were employed to determine local wall and local hot gas temperatures. In addition, a load cell was used to record liquid fuel mass loss rates during each test thus allowing the determination of the rates of heat release, if required.

2.2.2 Test Compartment B

For the preliminary tests the chamber was approximately of the same physical dimensions and construction as compartment 'A' with one major difference, namely the inclusion of a vision panel 840 mm wide by 800 mm high consisting of a double glazed unit positioned centrally on the front wall, as shown in Fig. 3. The compartment was also constructed so that additional combustible and noncombustible internal lining material could be included as shown in Fig. 4 where a melamine chipboard lining material covered the walls.

For all of the lining tests conducted in compartment B the instrumentation was positioned as shown in Fig. 4.

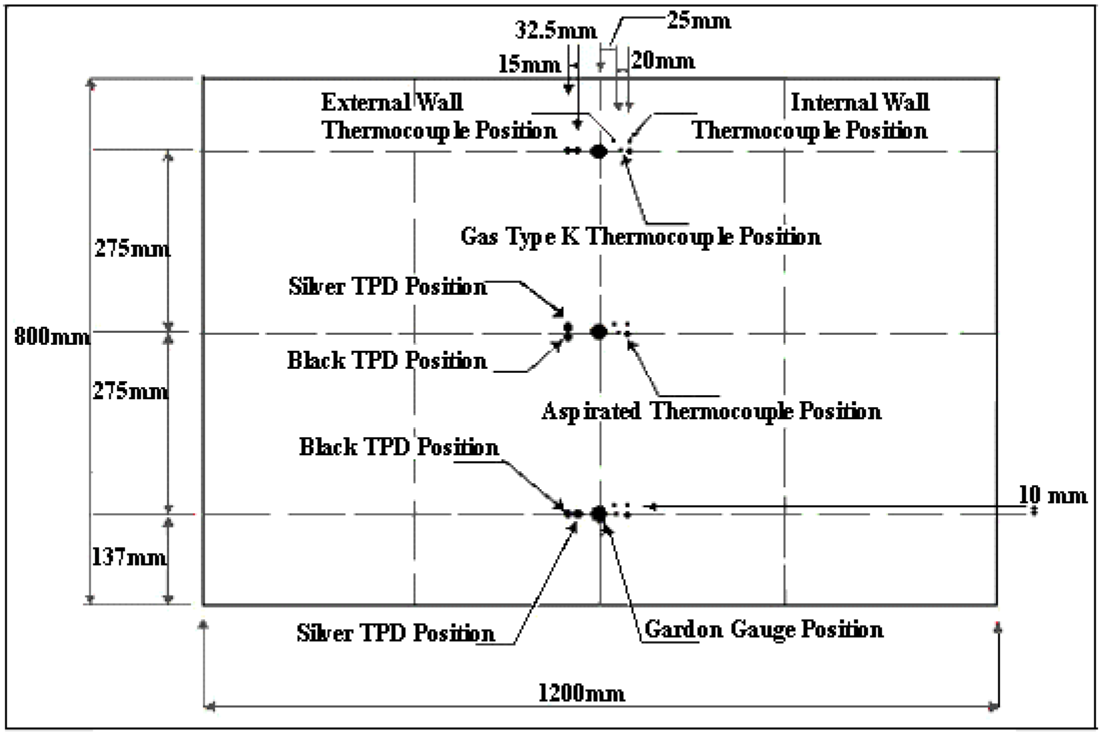

Fig. 2: Front wall instrumentation location Compartment A

Fig. 3: Compartment B with melamine chipboard linings test set up

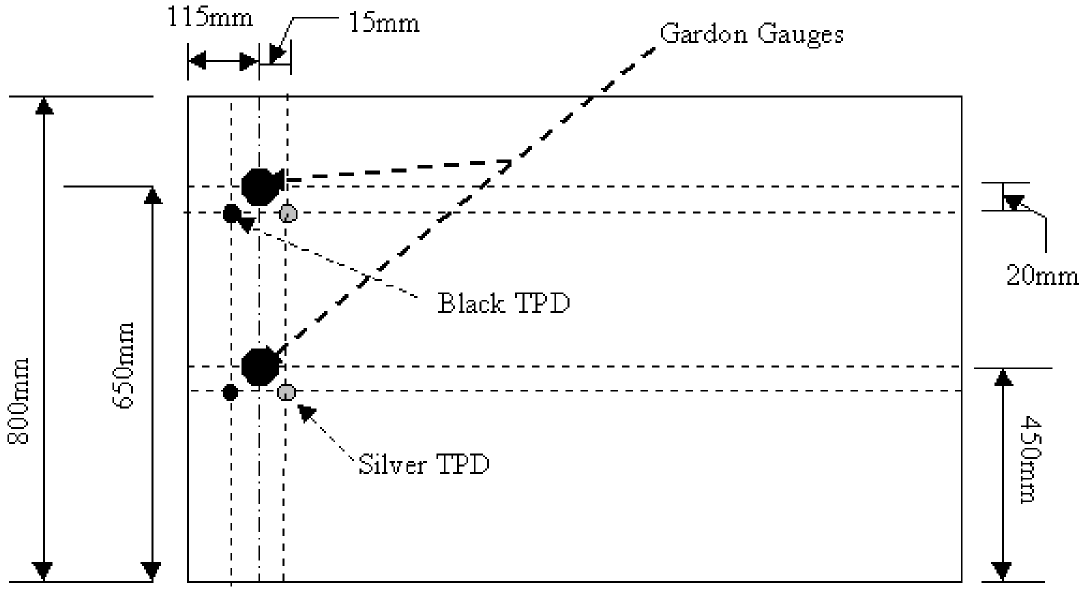

Fig. 4: Rear wall instrumentation location

2.2.3 Test Compartment C

In this case a full scale ISO test compartment was used. However, due to a desire not to interfere with an ongoing research programme the instrumentation was located on the left side of the west wall as shown in Fig. 5. In this case a Black TPD was set at a position 1560 mm high and 610 mm in from the side with the silver TPD located 25 mm higher. A total Flux Gardon gauge was located 30 mm higher again along the same vertical axis of the TPDs. The inclusion of the Gardon gauge was to collect flux data that would be compared with the TPD derived data.

3. RESULTS & ANALYSIS

Using data and observations collected during the test program for the two small and the large compartment fire tests, important issues in relation to the calibration of the TPDs, and the partitioning of the convective and radiative components of the incident heat flux will now be discussed.

3.1 TPD Calibration

From preliminary tests conducted and reported by Lennon & Silcock [1] it was concluded that the TPDs provided a crude but effective method for the measurement of incident heat flux, however, it was apparent that further development and assessment work was required. Thus, at this stage, it was decided to ignore the back conduction losses from the TPDs since according to Dillon [11] this heat transfer process only accounted for 5% of total losses for a similar device. An important feature of the TPD, is its ability to derive the convective component of the incident heat flux, however this cast doubts on the proposed calibration process, which used the radiant field of a cone calorimeter. This caused concern since in a real fire convection will also be present. These concerns refer not only to the TPDs but also to other common thermopile and thermocouple devices such as Gardon and Schmidt-Boelter type gauges.

Such concerns have led to the on going development of a convective heat flux calibration facility at NIST (see Holmberg et al. [12]) for heat flux sensors. Thus allowing direct comparisons of sensors in controlled convective and radiative environments. Previous calibration inaccuracies of at least ± 10% are removed by employing this calibration process. However the facility in its present state is limited to a maximum calibration convective flux of approx. 5 kWm^{-2}. Initially and to date TPDs measurements have been compared with Gardon gauges, the results of which, subject to the error in the estimation of convective and radiative fluxes, are assumed to have the related error of ± 10%.

To highlight the problems of calibration, the derived heat transfer coefficients from various tests were incorporated into the equations proposed by Kuo & Kulkarni [13] to minimise the errors induced in Gardon gauges calibrated in a radiation field, but employed in the mixed environment of a real compartment fire. However after employing test data derived from corner small scale fire tests the results seem to indicate that limitations exist in their proposed equations, which appear to be relevant for fires with only a very low convective environment. This is highlighted in Fig. 6, where the corrected total incident flux from the Gardon gauge (Final Gauge) obtained diverges increasingly with time from the uncorrected total flux measurements. This may of course, be due to the data obtained from the TPDs, however on a closer analysis of the equations, this seems unlikely.

3.2 Convection Component Data Analysis

Using equations developed during an analytical approach by Vatell [10], the analysis of which is given in appendix A in the context of the TPD device, values for the radiative and convective heat fluxes can be evaluated using the following expression.

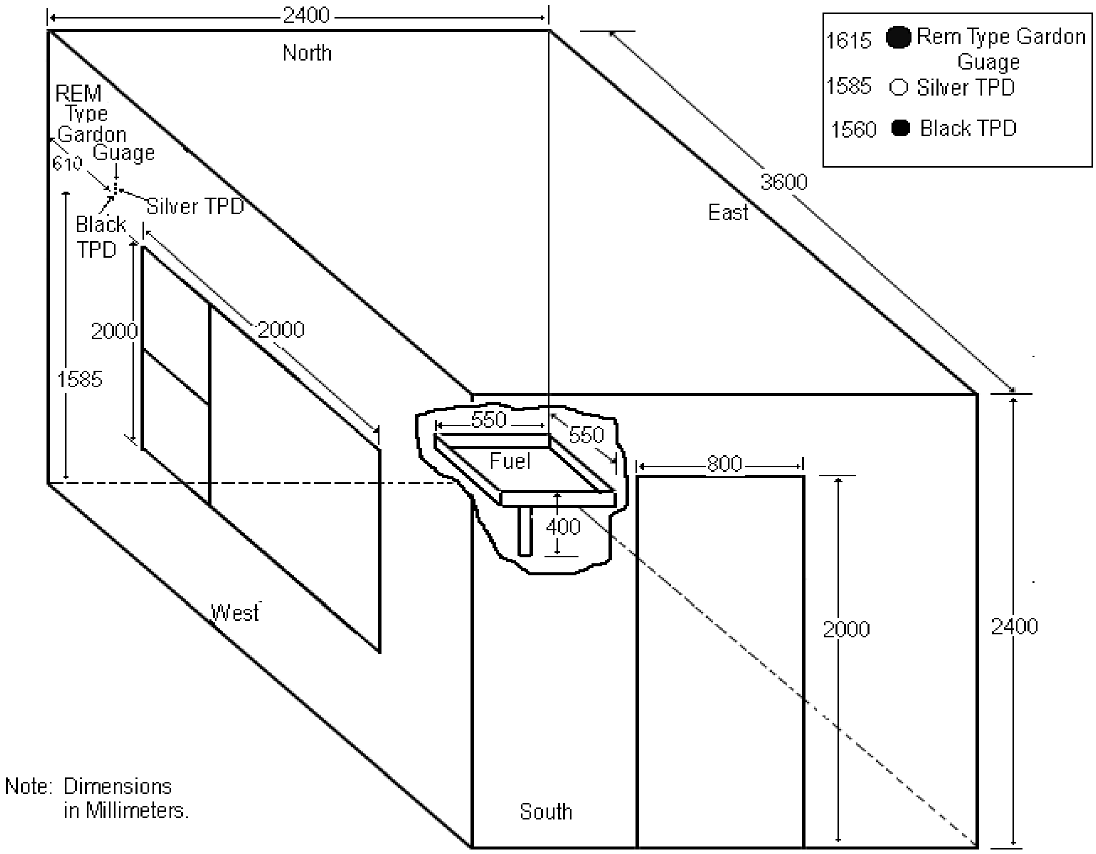

Fig. 5: Full scale ISO test compartment

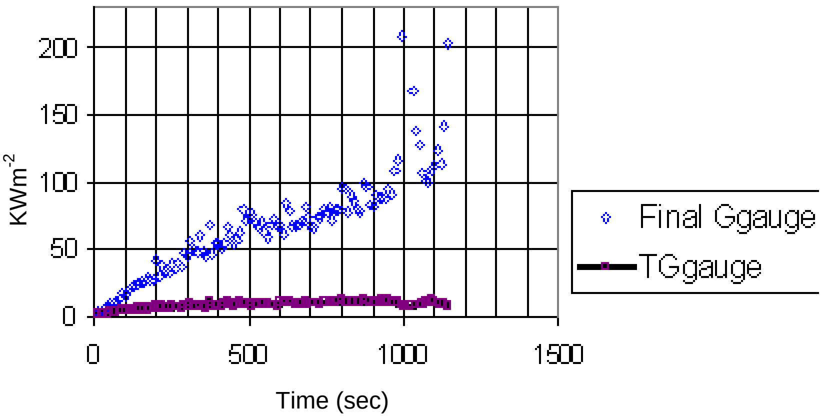

Fig. 6: Corner fire test. Unlined (Meths/Diesel mixture). Corrected total incident flux.

Namely:

$$q''_{rad} = (q''_b - q''_s)/(\varepsilon_b - \varepsilon_s) \quad (1)$$

$$q''_{con} = q''_b - \varepsilon_b\{(q''_b - q''_s)/(\varepsilon_b - \varepsilon_s)\} \quad (2)$$

Thus at any point in time, the convective, radiative and the total heat flux can be evaluated, i.e.

$$q''_t = q''_{rad} + q''_{con.} \quad (3)$$

3.2.1 Convection Component Analysis (Test Compartment A)

Fig. 7 illustrates the ratio of convective heat flux (q''_{con}) to the total incident heat (q''_t) for a Methylated/Diesel fuel mixture fire test. Here, except at the very early stages of the fire, and later where the diesel begins to burn, the relationship remains remarkably constant with the convection component dominant. Note the slight peak and then fall around 1000 seconds as the diesel begins to burn thus enhancing the radiative component.

Similarly the fluxes given by the TPDs data have been used to determine estimates of the experimental ratio (%qcon) for the percentage convective heat transfer to the total incident heat for a pure methylated spirits fire (Fig. 8). Whilst there may be some concerns regarding the accuracy of the gas temperature measurements, these preliminary and approximate results were nonetheless interesting. At the high position the percentage ratio remained relatively constant. However, at the mid position the same ratio was more variable with the convective component less dominant possibly due to the TPDs proximity to the neutral plane and thus the likelihood of unsteady conditions during the early stages of the fire and to systematic and random errors associated with the crude approach adopted to estimate the local heat transfer. Thus, by employing a larger number of the new TPDs compared to the Gardon gauge flux meters, a clearer and more detailed picture of the exposed surface fire flux field environment is possible. Such detail might prove valuable to fire modellers who are always seeking reliable and valid raw data to improve and validate their models.

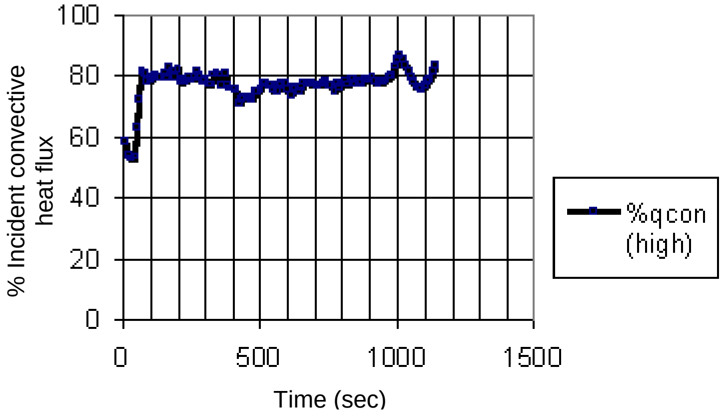

Fig. 7: % Convective heat transfer. Component of total. High position. Corner test (Meths/Diesel mixture)

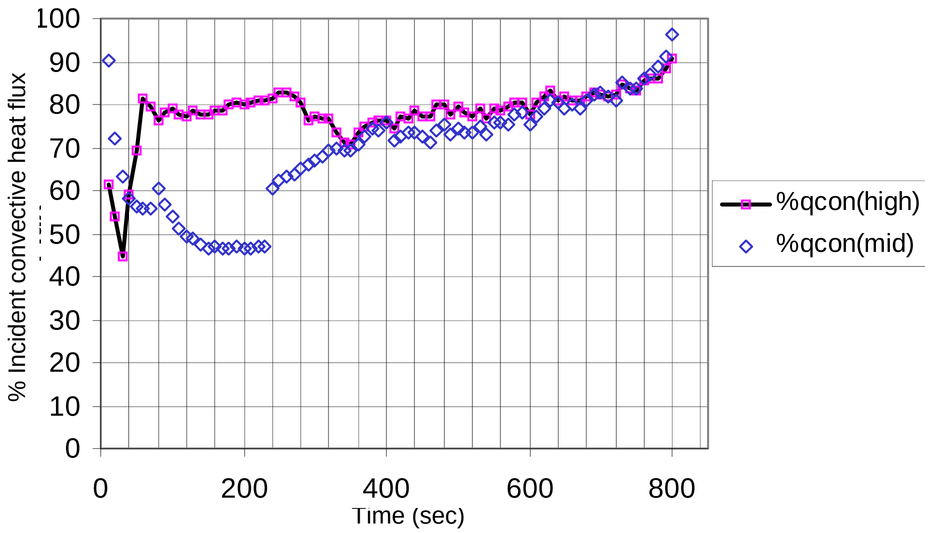

Fig. 8: Convective to total heat transfer ratio for Corner test (Meths fuel)

From the research conducted to date, it is clear that further development work is required in the area of incident flux determination and in the removal/ reduction both of systematic and random errors from the final data produced by the TPDs.

3.3 Lining Tests (Test Compartment B)

Taking the above work into account, additional investigative work as discussed earlier was conducted using a one third-scale enclosure where melamine faced chipboard and fire resistant chipboard linings respectively were used to provide the data necessary for the analysis of the response of the TPDs to the more realistic developing enclosure fire environment. Figs. 9 and 10 illustrate different stages in the development of melamine chipboard lined fire test-employing compartment B.

Fig. 9: Test Compartment B melamine chipboard lining. Developing fire. 50 seconds after ignition of fuel.

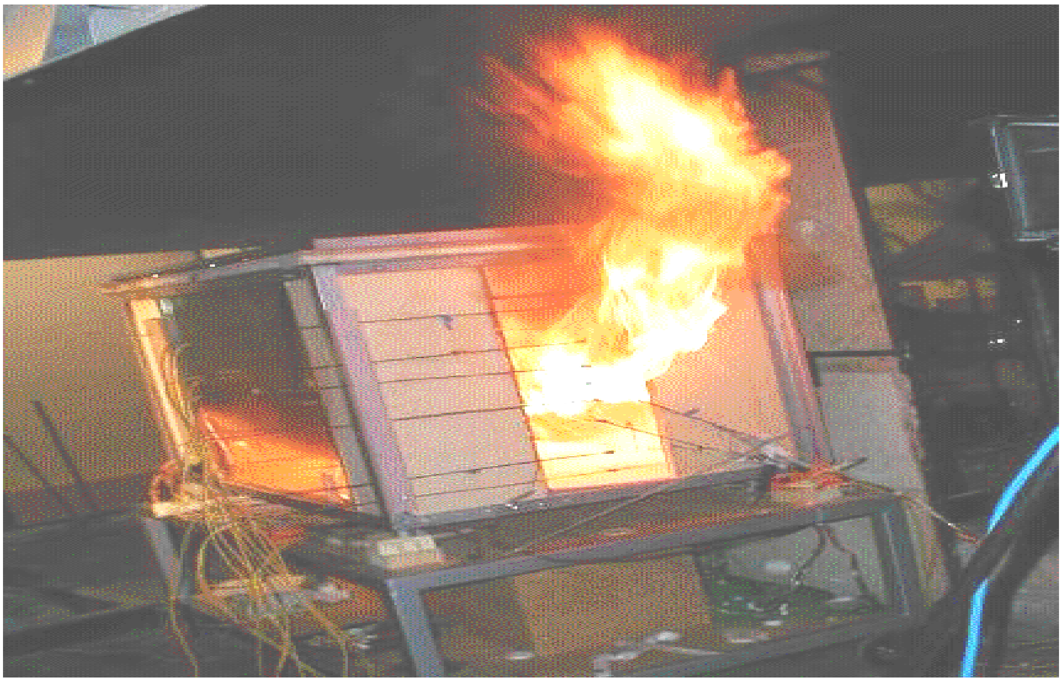

Fig. 10: Test Compartment B melamine chipboard lining. 600 seconds after ignition of the fuel.

In the case of the melamine chipboard linings tests, the results concluded that the TPDs [(qt) as labeled in the following graphs] produced accurate results when compared to total flux Gardon gauge (TGgauge) outputs during the early stages of the fires and up to the flashover event, no matter whether the linings were combustible or not (see Fig. 11).

Using this adaptation for the TPD calibration protocols, subsequent results were shown to be close to the Gardon gauge outputs, Fig. 12, i.e. when the TPD was embedded in the compartment lining material during the modified calibration process. The differences delivered by the modified calibration process of the TPD are clearly demonstrated in Figs. 11 and 12. However, this convergence of flux output still does not address the ever-present convection calibration problem and, in this particular case, differences in measurements between the two types of instruments may be due to the fact that it is not physically possible from a practical point of view to place the TPD and the Gardon gauge in exactly the same location (See Fig. 4).

Using the modified calibration methodology the total fluxes recorded by the TPD's during the tests using fire resistant chipboard produced results as shown in Fig. 13. Here the total incident fluxes recorded by the total Gardon gauge and the TPDs are very similar. This reinforces the adopting of the modified Calibration TPD process to suit the expected linings and appears to enhance the accuracy of the data subsequently produced.

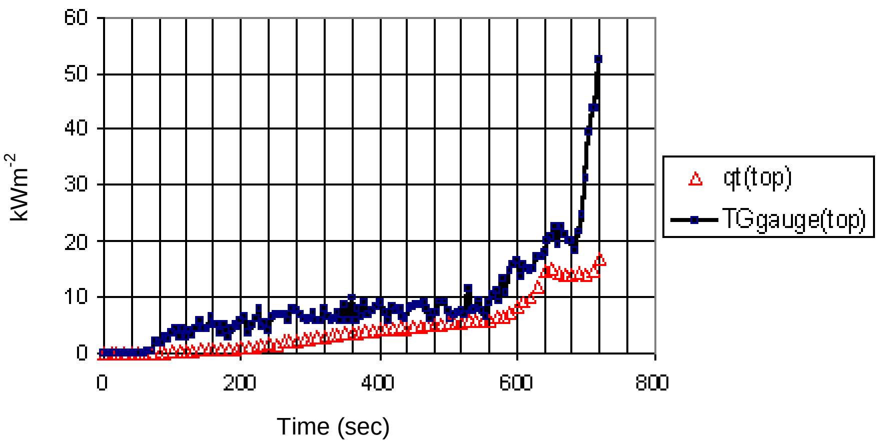

Fig. 11: Corner fire test. Top position. Results employing the initial TPD calibration method. Melamine chipboard linings.

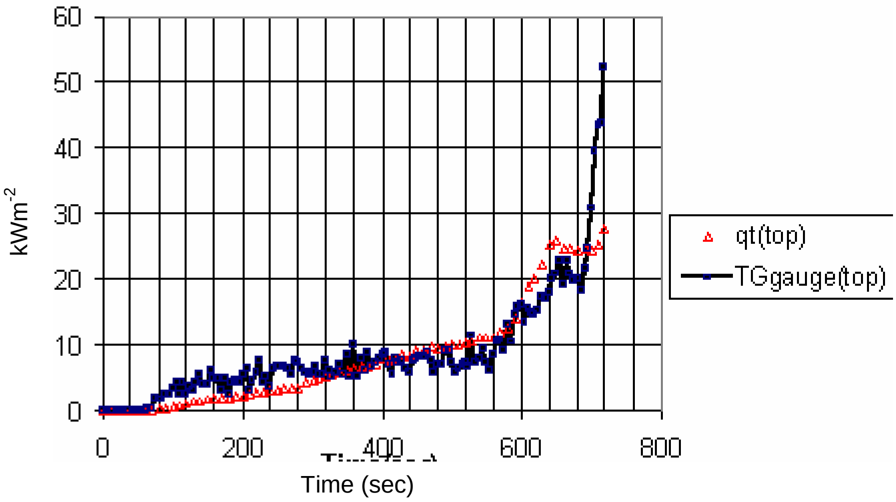

Fig. 12: Corner fire test. Top position. Results employing modified TPD calibration method. Melamine chipboard linings.

The results obtained from the lining tests also demonstrated the ability of the TPDs to cope with different fire environments i.e. from fires within the enclosure when insulated Fibrefax wall linings were used, to walls of combustible chipboard. However, results still seem to suggest convection-dominated environments particularly during the early stages of the fire. However, Fig. 14 shows the radiation component increasing as the linings begin to ignite and burn causing the emissivity of the fire gases to change. In addition, in the more severe environments the accuracy of the TPDs declines after the first 15 to 20 minutes due in part to the low emissivity device deteriorating due to melting and delaminating of the foil if located adjacent to the flames in severe fires and/or dulling of the surface due to smoke particles settling on its face. The overcoming of these problems will comprise a major element of future research and development of the Thin Plate Device.

3.4 Full Scale Testing (Compartment C)

In this case, full scale testing of the TPD, to date, has been very limited with one full-scale test carried out for one TPD position at the top of the front wall between the sidewall and the window (see in Fig. 5). It must be noted that in this case the TPD being at slightly different heights compared to the Gardon gauge did not provide ideal conditions for the comparison of derived and measured heat fluxes. Nevertheless Fig. 15 indicates, as anticipated, that away from the fire there was a convection dominated environment typical of preheating conditions in an enclosure under the thermal impact of a corner fire.

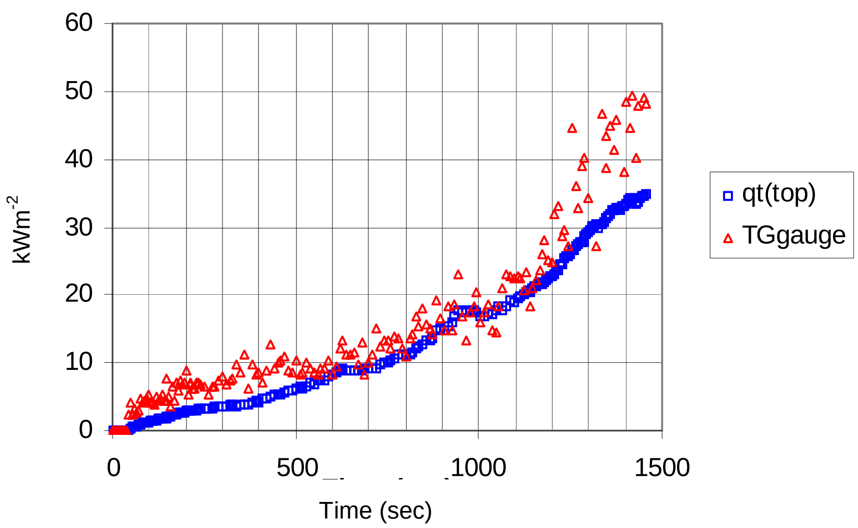

Fig. 13: Corner fire test. Top position. Fire resistant chipboard. Results employing modified TPD calibration method.

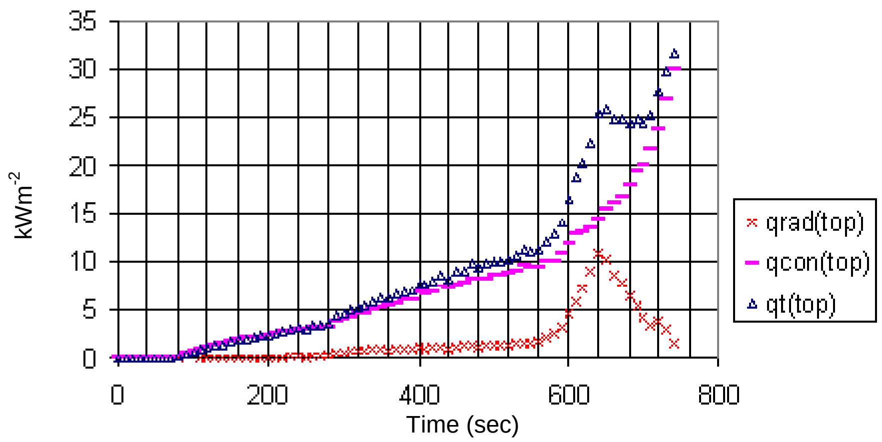

Fig. 14: Convective to radiative heat flux partitioning employing modified TPD calibration method. Melamine chipboard linings.

Fig. 16 also shows excellent agreement between the fluxes determined by both the TPDs and the Gardon Gauge in the same test and gives a clear indication of the differing response behaviour of each device where the Gardon gauge due to its mode of construction possesses a lower time constant compared to the TPD.

4. DETERMINATION OF EXPERIMENTAL ERRORS

Detailed description of the evaluation of the experimental error is given in Appendix B where the relevant theory is utilized with TPD derived data.

5. CONCLUSIONS

It is clear that despite of the considerable amount of research undertaken, with respect to the direct evaluation of the incident flux in real time using costly Gardon and Schimdt-Boelter gauges which require cooling and data correction, that problems of calibration and the fragile nature of their construction limit their use in hostile fire environments. However, it would appear that the low cost robust TPD, unlike the Gardon gauge which require cooling [13] and cool surface correction [11], has the potential to assist in the measurement of incident flux and thus in the quantification of fire severity. In addition the following conclusions to be drawn from the analysis of data on the performance of the TPD suggest that:

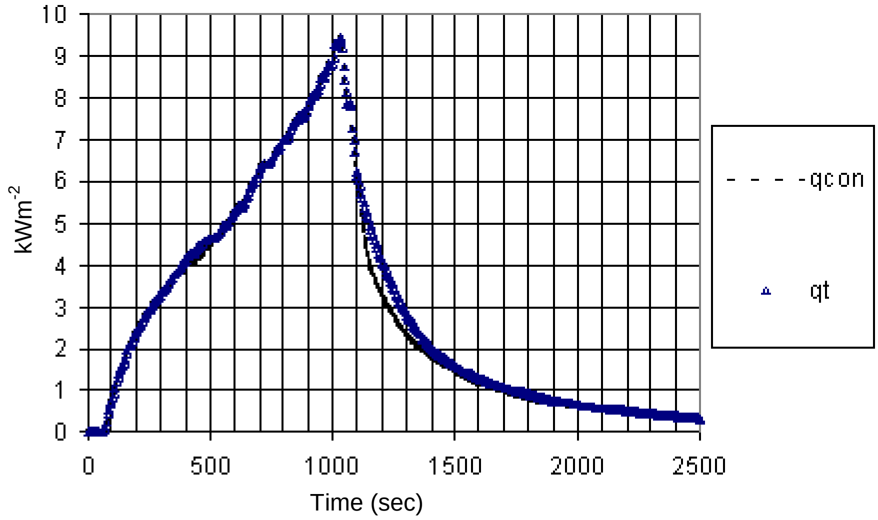

Fig. 15: Fire resistant chipboard Linings. Comparsion of convective and Total heat flux.

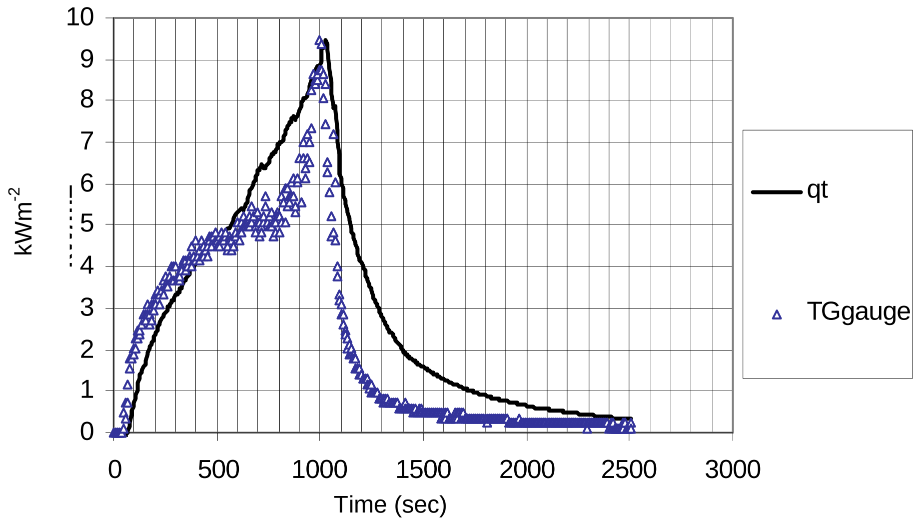

Fig. 16: Fire resistant chipboard linings. West wall beside window. High position. Comparison with Total Gardon Gauge output.

- The TPDs have the capability to partition the convective and radiative components of heat flux with respect to real time.
- The TPDs are physically robust, cheap and are capable of coping with very different compartment fire environments.
- The response times are satisfactory for fire safety engineering research purposes.
- Improved accuracy in results can be achieved when the TPDs are calibrated with the same linings as used during tests.
- The use of the TPD devices removes the need for costly and cumbersome cooling apparatus for the heat flux gauges.
- These new devices unlike other heat flux gauges do not require the calculation of cool face loss correction factors.

6. RECOMMENDATIONS

Again from the above analysis and conclusions it is recommended that:

- The development of a facility capable of the calibration of the incident heat flux-measuring devices in a convective and/or mixed environment employing the same high flux levels as anticipated in real enclosure fires is required.
- Further research into the TPDs ability to measure varying incident heat fluxes associated with a compartment fire taking account such parameters as ventilation openings and scaling be undertaken.

ACKNOWLEDGEMENTS

We wish to thank the staff from the research, technical and administrative at the FireSERT centre for their assistance and cooperation throughout the time spent carrying out this research work.

NOMENCLATURE

ε emissivity
α absorbtivity
q" total thermal flux available to the TPD discs, kWm^{-2}
$q"_{con}$ convective component available for each TPD surface, kWm^{-2}
$q"_{rad}$ available radiative component, kWm^{-2}
$q"_1(t)$ & $q"_2(t)$: total thermal flux available to discs 1 and 2 at time period t, kWm^{-2}
Tggauge: measured total incident flux from the Gardon Gauge, kWm^{-2}
Final Gauge: derived values from total Gardon gauge output corrected by employing equations from reference 11 and test data for use in mixed field environment, kWm^{-2}
q_b heat flux signal from black painted sensor, kWm^{-2}
q_s heat flux signal from silver sensor, kWm^{-2}
ε_b emissivity of the black surface
ε_s emissivity of the silver surface

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APPENDIX A

In the following paragraph the theory used to predict incident flux values from the thin plate devices is outlined.

Assuming grey body characteristics it can be assumed that $\alpha_\lambda = \varepsilon_\lambda$ when the emissivity ε and absorbtivity α are independent of wavelength, magnitude and direction of incident radiation. Employing an energy balance approach for the surface of each disc, it follows that the total thermal flux available to the discs q" can be expressed as:

$$q'' = \alpha\, q''_{rad} + q''_{con.} \tag{1}$$

Or:

$$q'' = \varepsilon\, q''_{rad} + q''_{con.}$$

The convective component q''_{con} available for each surface is considered the same to each surface due to their closeness and similar orientation (see Fig. A1), writing eqn. (1) for each surface having respective emissivities ε_1 and ε_2 i.e.

$$q''_1 = \varepsilon_1 q''_{rad} + q''_{con.} \tag{2}$$

$$q''_2 = \varepsilon_2\, q''_{rad} + q''_{con.} \tag{3}$$

When $\varepsilon_1 > \varepsilon_2$ it follows that,

$$(q''_1 - q''_2) = (\varepsilon_1 - \varepsilon_2)\, q''_{rad}.$$

Therefore:

$$q''_{rad} = (q''_1 - q''_2)/(\varepsilon_1 - \varepsilon_2) = \tan\alpha. \tag{4}$$

Substituting eqn. (4) into eqn. (2) results in the following expression,

$$q_1'' = \{(q''_1 - q''_2)/(\varepsilon_1 - \varepsilon_2)\} + q''_{con}.$$

Then:

$$q''_{con} = (\varepsilon_1 q''_2 - \varepsilon_2 q''_1)/(\varepsilon_1 - \varepsilon_2) = q''_1 - \varepsilon_1\{(q''_1 - q''_2)/(\varepsilon_1 - \varepsilon_2)\} \tag{5}$$

Therefore:

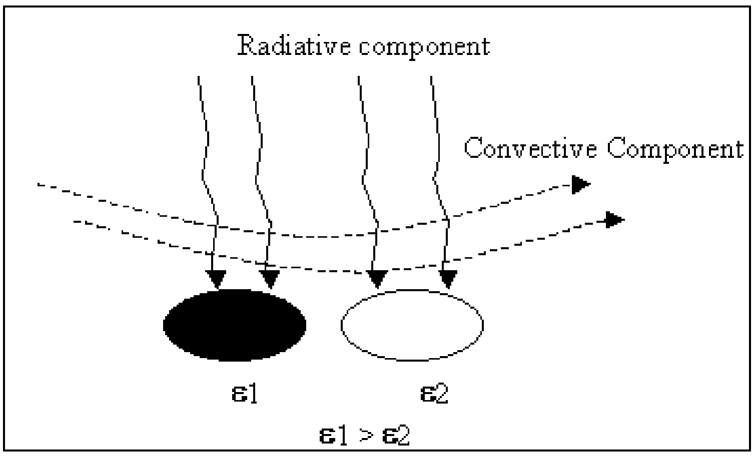

Fig. A1: TPD theoretical principle of operation

$q''_{con} = q''_1 - \varepsilon_1 q''_{rad}$. (6)

The total incident flux can now be written as,

$q_t = q''_{con} + q''_{rad}$. (7)

Therefore:

$q_t = q''_1 - \varepsilon_1 q''_{rad} + q''_{rad.}$

And:

$q_t = q''_1 + (1 - \varepsilon_1) q''_{rad.}$

So:

$q_t = q''_1 + \{(1 - \varepsilon_1)(q''_1 - q''_2)/(\varepsilon_1 - \varepsilon_2)\}$. (8)

A graphical interpretation of the above equation is given in Fig. A2.

Thus, at any point in time $q''_1(t)$ and $q''_2(t)$ can be determined experimentally and analysed using the relevant equation as discussed above to yield both the convection and radiation components respectively.

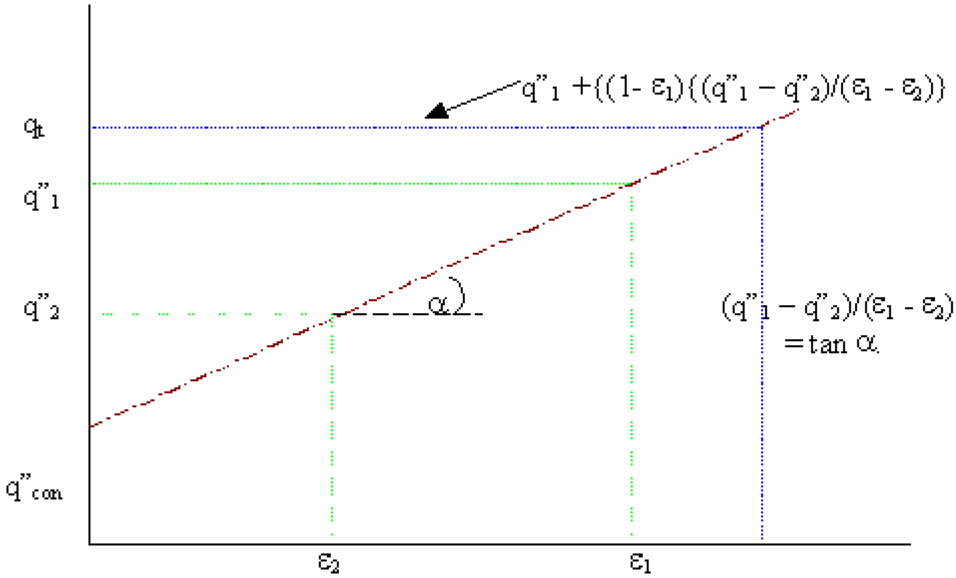

Fig. A2: Graphical interpretation of theoretical analysis

APPENDIX B

EVALUATION OF EXPERIMENTAL ERRORS

B.1 Experimental Error Formulation

Using the expressions derived in Appendix A for the convective, radiative and total incident flux levels the following expressions were derived to estimate the experimental errors associated with the derived values i.e. q''_b and q''_s , the fluxes recorded by the black and silver surfaced TPD's and correspond to q''_1 and q''_2 respectively as used in Appendix A.

B.1.1 Error in Radiative Flux

The factional error in the radiative flux:

$$\frac{\Delta \dot{q}''_{rad}}{\dot{q}''_{rad}} = \sqrt{\frac{\left(\Delta \dot{q}''_b{}^2 + \Delta \dot{q}''_s{}^2\right)}{\left(\dot{q}''_b - \dot{q}''_s\right)^2} + \frac{\left(\Delta\varepsilon_b{}^2 + \Delta\varepsilon_s{}^2\right)}{\left(\varepsilon_b - \varepsilon_s\right)^2}}$$

Where:

$$\dot{q}''_{rad} = \frac{\dot{q}''_b - \dot{q}''_s}{\left(\varepsilon_b - \varepsilon_s\right)}$$

B.1.2 Error in Convective Flux

The factional error in the convective flux:

$$\frac{\Delta \dot{q}''_{con}}{\dot{q}''_{con}} = \sqrt{\frac{\Delta\varepsilon_b{}^2 + \Delta\varepsilon_s{}^2}{\left(\varepsilon_b - \varepsilon_s\right)^2} + \left\{\frac{\left(\varepsilon_b \dot{q}''_s\right)^2\left[\left(\frac{\Delta\varepsilon_b}{\varepsilon_b}\right)^2 + \left(\frac{\Delta \dot{q}''_s}{\dot{q}''_s}\right)^2\right] + \left(\varepsilon_s \dot{q}''_b\right)^2\left[\left(\frac{\Delta\varepsilon_s}{\varepsilon_s}\right)^2 + \left(\frac{\Delta \dot{q}''_b}{\dot{q}''_b}\right)^2\right]}{\left(\varepsilon_b \dot{q}''_s - \varepsilon_s \dot{q}''_b\right)^2}\right\}}$$

Where:

$$\dot{q}''_{con} = \frac{\varepsilon_b \dot{q}''_s - \varepsilon_s \dot{q}''_b}{\varepsilon_b - \varepsilon_s}$$

B.1.3 Error in Total Incident Flux

The factional error in the total flux:

$$\Delta \dot{q}''_t = \sqrt{\Delta \dot{q}''_{rad}{}^2 + \Delta \dot{q}''_{con}{}^2}$$

Where:

$$\dot{q}''_t = \dot{q}''_{rad} + \dot{q}''_{con}$$

B.2 Application of Error Formulation

An estimation of the experimental errors associated with the incident fluxes have been undertaken using data for $\dot{q}''_b$ and $\dot{q}''_s$ at a time of 210 seconds after the start of a test.

Then:

$\dot{q}''_b = 37.1\ \mathrm{kWm^{-2}}$ and $\dot{q}''_s = 33.8\ \mathrm{kWm^{-2}}$

Assuming:

$\varepsilon_b = 0.96$ and $\varepsilon_s = 0.10$

And that errors in $\dot{q}''_b$ and $\dot{q}''_s$ are as follows.

$\Delta\dot{q}''_b = 2.6\ \mathrm{kWm^{-2}}$ and $\Delta\dot{q}''_s = 2.4\ \mathrm{kWm^{-2}}$

Note: These include both the systematic errors associated with the initial calibration flux field and the actual random error associated with the actual calibration of the TPD's.

If the errors associated with ε_b and ε_s can be ignored (not a difficult decision in this case) the resulting errors were evaluated as: $\Delta\dot{q}''_{con} = 2.7\ \mathrm{kWm^{-2}}$, $\Delta\dot{q}''_{rad} = 3.3\ \mathrm{kWm^{-2}}$ and $\Delta\dot{q}''_{Tot} = 4.26\ \mathrm{kWm^{-2}}$.

This results in the following estimations for the incident fluxes for this case/scenario.

$$\Delta\dot{q}''_{con} = 33.43 \pm 2.70\ \mathrm{kW\,m^{-2}}$$

$$\Delta\dot{q}''_{rad} = 3.80 \pm 3.30\ \mathrm{kW\,m^{-2}}$$

$$\Delta\dot{q}''_{t} = 37.25 \pm 4.30\ \mathrm{kW\,m^{-2}}$$

This suggests that radiative flux levels less than 5.0 kWm^{-2} are subject to experimental errors, which cause such results to be less reliable.