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Temperature and heat flux measurement techniques for aero-engine fire test: a review

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Abstract. This review is made of studies whereby some types of fire test measuring instrument were compared based on their mode of operation, sensing ability, temperature resistance and their calibration mode used for aero-engine applications. The study discusses issues affecting temperature and heat flux measurement, methods of measurement, calibration and uncertainties that occur in the fire test. It is found that the temperature and heat flux measurements of the flame from the standard burner need to be corrected and taken into account for radiation heat loss. Methods for temperature and heat flux measurements, as well as uncertainties analysis, were also discussed.

1. Introduction

Temperature and heat flux measurements are important factors that need to be considered in fire test experiment for aero-engine applications. These two factors require accurate sensors that can easily sense and correctly read the inputs and outputs. Therefore, design and implementation of the sensors and calibration system is a complex process that requires attentive precautions to ensure accuracy in the measurements. There are many types of temperature and heat flux measuring devices that are used for fire test [1]. A good understanding of temperature and heat flux measuring devices for heat transfer to solids exposed to fire conditions is important for the fire test in building structures and aerospace industries. There are some uncertainties that arise in measuring the different forms of convection and radiation heat flux on the standard type of test that should be carried out, and on the temperature and load bearing capacity of structural components, as well as time to ignition and burning characteristics of materials and products [2].

The main issues associated with measurement of flame temperature and heat flux are the sensors in the measuring devices and the ability of the devices to measure the range of temperatures in the fire test. To the authors' knowledge, there is no available literature that reviews the temperature and heat flux measurements used for aerospace applications. The main objectives of this review are to identify devices for measuring temperature and heat flux by choosing the proper sensors according to their characteristics, to quantify the measurement errors and the problems associated with these devices, and to assess issues, methods, calibration and uncertainty on temperature and heat flux measurements in fire test techniques for aerospace engineering applications.

2. Standard fire test for aerospace applications

The standard fire test techniques used in aero-engine fire certification are explained in the ISO2685 [3] and AC20-135 [4].

2.1. ISO2685 fire test standard

ISO2685 standard specifies the test conditions applied to all components, equipment and structures located in zones designated as “fire zones” and built to satisfy the minimum level for resistance to fire. The standard does not relate to the resistance to fire outside the designated fire zones, the flammability requirements or to those conditions induced by the flame coming from the combustion chamber. Abu Talib *et al.*[5] reported that ISO propane-air burner is frequently used in UK to certify critical engine components that will be exposed to the danger of aircraft engine fires. Meanwhile, kerosene burner is widely used in the US and this is also specified in ISO 2685. The standard defines the designated fire zone as the region of an aircraft, as the compartment containing main engines and auxiliary power units, designated in accordance with the requirements of the approving authorities. The flame having the characteristic of 1100°C ± 80°C temperature and 116 kW/m^2 ± 10 kW/m^2 heat flux. In ISO 2685, the burner head must act as the flame stabilizer and prevents any flashback into the plenum chamber containing the combustible mixture. The burner is made up of 373 copper tubes, which are cooled by air flowing around them. The cooling air is supplied through 332 holes at the flame head, maintaining the burner temperature at the level required for the test. The cooling air shall be well distributed within the structure of the flame head in order to maintain the burner temperature at the required level. Air and gas are introduced and mixed in a small chamber, the mixed gas and air enter the larger plenum chamber before reaching the flame head.

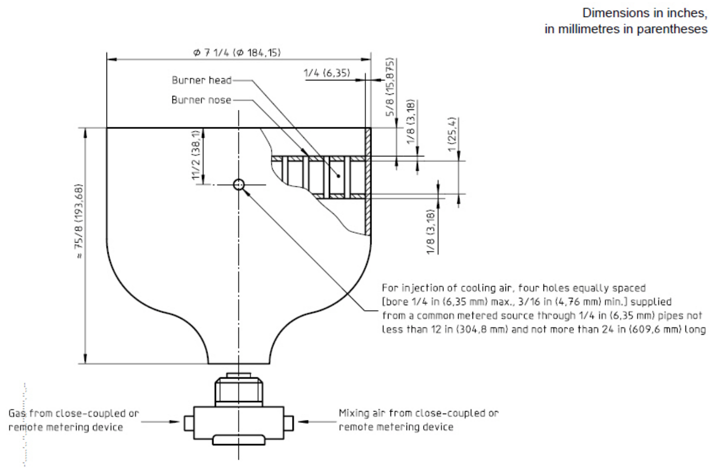
Figure 1 shows the arrangement of propane-air burner, which shows the chamber where air and gas fuel are mixed at the upper base of the burner, then the mixture is passed into 1/8-inch copper tubes with a bore of 0.07 inch. The secondary air (cooling air) that is used to cool the burner and maintain the flame temperature goes through a 0.102 inch. Figure 1(a) is the main body of the burner, which is made from copper that contains fuel and an air entrance with a small chamber where fuel and air pre-mixed together and moves to plenum chamber. In addition, there is also a hole drilled at the top of the burner whereby a secondary air is introduced to the burner that provides a coolant air that stabilizes the flame temperature to be uniform. At the top of the main body is a plate that contains the burner head and burner nose as shown in Figure 1(b). The plate contains 373 copper tubes that mix the fuel and air pass through it, and another 332 holes for secondary pass through [3]. The dimensions of the stated instruments are shown in the figures.

2.2. AC 20-135 fire test standard

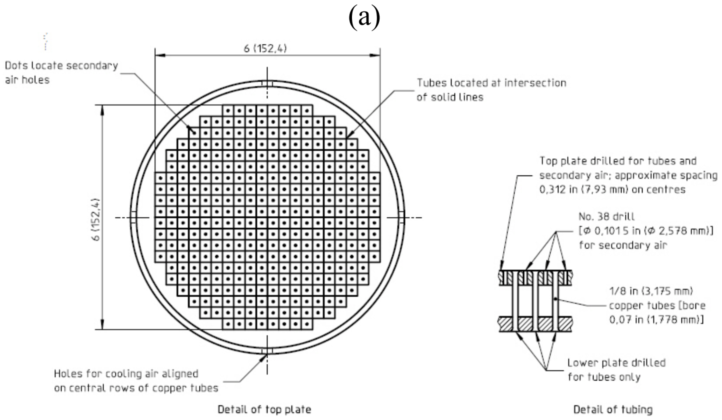
This is another standard that explains the methods used in determining the conformity with the power-plant fire protection prerequisite of the Federal Aviation Regulations (FAR). The standard provides procedures for the fire testing of materials and components used in the propulsion engines and APU installations, and near the fire designated zones. Although the terms are considered in classifying the material according FAR, these two terms are "fireproof" and "fire resistant," but in this standard the level of heat intensity, temperature levels, exposure time, or an appropriate wall thickness and other dimensional features were not clearly stated. When the materials are coated, composed of laminated composites and metal honeycomb for acoustically treated ducting, cowling and other components that are element of the nacelle firewall, shows the ability to withstand fire [6]. The definition of fireproof and fire resistant are as follows:

- Fireproof: the ability of a material or component to resist a flame temperature of 1093°C flame (±65.6°C) for 15 minutes minimum, and still it performed its function. When materials and parts used in an enclosed fire within designated fire zones, it means that the material or part will be used under conditions likely to occur in such zones and will resist a 1093°C flame (±65.6°C) for 15 minutes minimum.

- Fire Resistant: the ability of a material or component to resist a flame temperature of 1093°C flame (±65.6°C) for 5 minutes minimum and still it performed its function. When a materials and parts used in an enclosed fire within designated fire zones, it means that the material or part will be used under conditions likely to occurs in such zones and will resist a 1093°C flame (±65.6°C) for 5 minutes at least.



(a)



(b)

Figure 1. Configuration of propane burner (reproduced from ISO2685 [3])

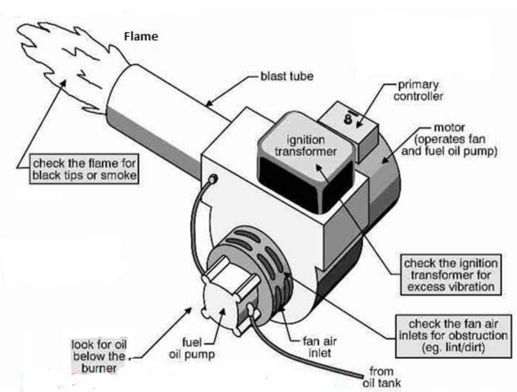


Figure 2. Oil burner [7]

3. Temperature measurement
The flame temperatures were measured at appropriate axial distance from the burner to verify that the conditions of the standard flame are achieved [8]. This section explains the methods, calibration and issues of temperature measurement.

3.1. Methods of temperature measurement
Comprehensive temperature plan was acquired if sole thermocouple over the measurement plane of the ISO burner was traversed. The measured values of temperature, heat flux and a sample in ISO 2685 propane-air burner needs to be taken at a distance of 75 mm (3 inch) from the burner face. Samir and Ryan [9] reported an experiment that was conducted on 3-inch x 3-inch samples where the temperature distribution was found to be uniform and the mean temperature reading of 1119°C were obtained. Among the types of temperature measuring devices are thermocouple, liquid-in-glass thermometers, resistant temperature detectors (RTDs), thermistors and optical pyrometers [1]. Thermocouple is the most common sensor that determines the temperature in fire test, the circuit is made up of two wires of different metals or their alloys that are joined together at one end and open at the other end, an electromotive force (EMF) is generated due to the voltage differential between the open ends when the junction is heated. The voltage differential between the open wire terminals is the outcome of the temperature differences connecting the joints. These two junctions are the hot and cold junctions that are the measuring and reference junctions respectively as shown in Figure 3(a) [1].

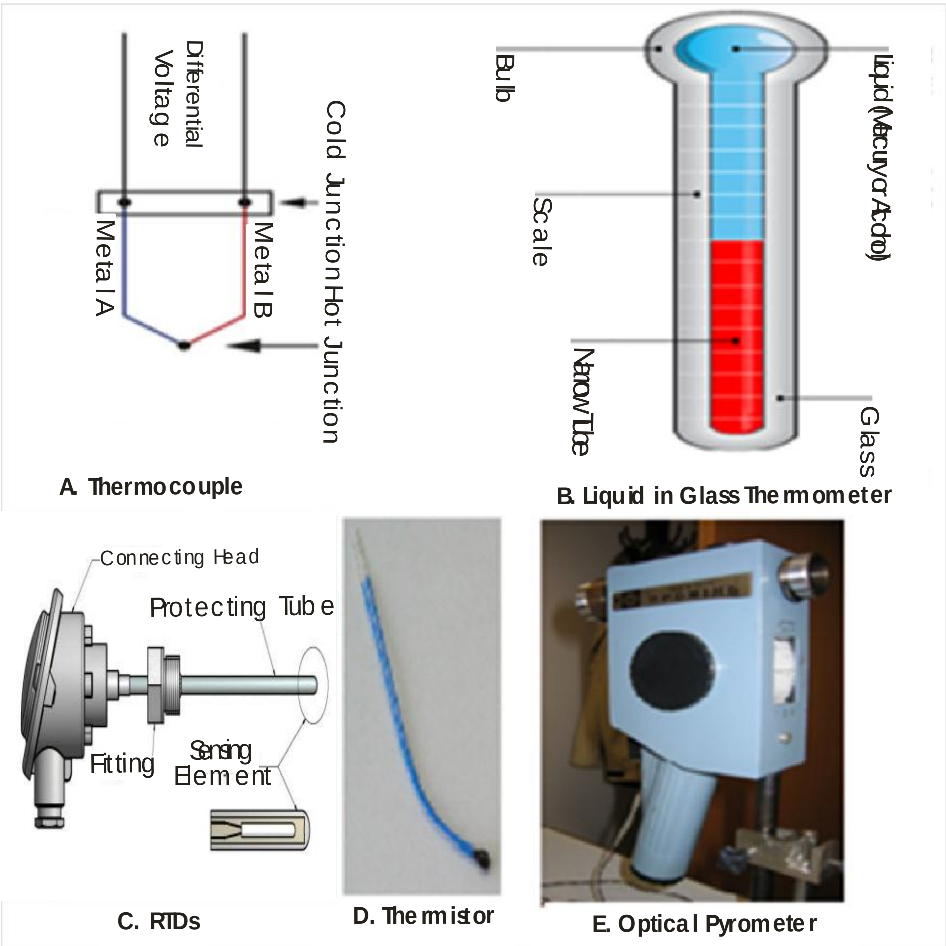


Figure 3: Types of temperature measuring devices: (A) thermocouples [10], (B) liquid in glass thermometer [11], (C) resistant temperature detector [12], (D) thermistor [13] and (E) optical pyrometer [14]

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There are different types of thermocouples used in measuring the temperature and when these thermocouples are protected, they can withstand the working temperature range as listed in Table 1. Type T thermocouple is applicable to the low temperature ranging from 0 to 350°C and it is a stable thermocouple which has a very good repeatability between a temperature range of -200 to 200°C. It has a standard accuracy of ±0.75% with special limit of error of ±0.4% with typical accuracy of 1°C. Meanwhile, Type J thermocouple is the type of thermocouple that has a short life span at very high temperature. It cannot withstand high temperature, where it can only withstand moderate temperature. The temperature range is greater than the temperature ranges of T type and it is also well suited to oxidizing atmosphere. It has a standard accuracy of ±0.75% and a special limit of error of ±0.4% with typical accuracy of 2.2°C. Type E thermocouple has a moderate temperature range which is stable with good operating range in oxidizing atmosphere. It has a standard accuracy of ±0.5% with special limit of error of ±0.4% with typical accuracy of 1.7°C. Meanwhile, Type K thermocouple which is usually Chromel/constant, normally has good corrosion resistant with a good operating temperature range. It can withstand a temperature of up to 1260°C and it is not expensive when compared with other types that have higher temperature range. It is partially having radiation hardness with a standard accuracy of ±0.75% with special limit of error of ±0.4% and with typical accuracy of 2.2°C. Type N thermocouple can withstand a high temperature with good corrosion resistant and good oxidation. It has a standard accuracy of ±0.75% with special limit of error of ±0.4% and with typical accuracy of 2.2°C. Meanwhile, Type R thermocouple is used both on high and low temperature application. It has a higher percentage of Rhodium than Type S thermocouple. Hence, it is more expensive than the other types of thermocouples. This type of thermocouple has high accuracy and stability. It moderately produces higher output, and has a standard accuracy of ±0.25% with special limit of error of ±0.1% and typical accuracy of 1.5°C. Type S thermocouple can be used in inert and oxidizing atmosphere up to 1600°C. It can be used both for high and low temperature application due to its high accuracy and stability. It has a standard accuracy of ±0.25% with special limit of error of ±0.1% and with typical accuracy of 1.5°C. Furthermore, Type B thermocouple has high temperature application, with high level of accuracy and stability. It has a low output at a temperature, which is lower than 600°C. It has a standard accuracy of ±0.5%, with special limit of error of ±0.25% and with typical accuracy of 5°C at 1000°C [16].

Table 1. List of thermocouple types and its working temperature range [15]

Thermocouples	Temperature Range (°C)
T	0 – 350
J	95 – 760
E	95 – 900
K	95 – 1260
N	95 -1260
R	870 -1450
S	980 – 1450
B	871 – 1704

Liquid-in-glass thermometer is the other type of sensor used to measure the fire temperature. It has a sealed bulb connected to glass capillary in the vertical stem and because of the development of the liquid rises in the capillary; temperature growth was developed, as shown in Figure 3(B). A resistant temperature detector (RTDs) uses metals especially Nickel or Nickel alloy for its high temperature resistance as the measuring instrument. It changes when temperature increases due to its positive change in electrical resistance; it is chemically stable and has high resistivity, as shown in Figure 3(C).

Thermistor is closely related to RTDs but has semiconductors that have electrical resistance. It can be used on small temperature of maximum of 100°C as shown in Figure 3(D). On the other hand, the optical pyrometer can sense the heat temperature of solid without touching the solid, the sensor sense thermal radiation emitted for the required area surfaces [1], the diagram in shown in Figure 3(E).

Thermochromic liquid crystals have been used to measure full surface temperature distribution [17]. The TLCs are coated on the model surface in which temperature distribution is to be determined by colour-temperature relationship and imaging, colourimetry, illumination, hysteresis, film thickness and aging that are related to calibration were studied. The images of different coloured for TLCs were recorded by digital video cameras [18, 19]. Another temperature measuring device is infrared camera that is non-contact temperature measuring device. Its advantages include measuring high temperature, high speed, able to measure the temperature of moving parts, no energy was lost in measurement and the sensor must be protected from dust and condensing liquid [14].

3.2. Calibrations of temperature measurements

Thermocouples rake was used to calibrate the flame temperature with an unprotected bead. Currently, there is no uniformity on the size of thermocouples (TC) as reported in [20, 21]. AC 20-135 specifies an acceptable sheath diameter to be used in calibrating thermocouple from 1/16-inch to 1/8- inch; while the ISO2685 standard uses a thermocouple of 0.12 inch sheath diameter. Furthermore, there are differences in measuring flame temperature using the two standards for the calibration requirement, whereby ISO2685 standard requires a standard temperature of 1100°C±80°C, while AC20-135 uses an average temperature of 1093°C±83°C. The thermocouples readings were recorded in data logger and the stand of the rake were placed above the centre line of the burner for correct calibration. The average value of the number of thermocouple used is taken as the values that the standard used [22]. Samir *et al.* [20] investigated the effect of thermocouple size on flame calibration, were two different sizes were investigated, the sizes investigated were 1/8 and 1/16-inch sheath diameter as shown in Figure 4. These thermocouples had AWG 28 wires with 0.012 inch diameter bead. The thermocouples sizes used in this experiment were acceptable for the calibration under AC20-135 regulations, which specify an acceptable thermocouple wire size range of AWG 20-30, but it was found out that the one with smaller sheath diameter give more acceptable result than the bigger one [4].

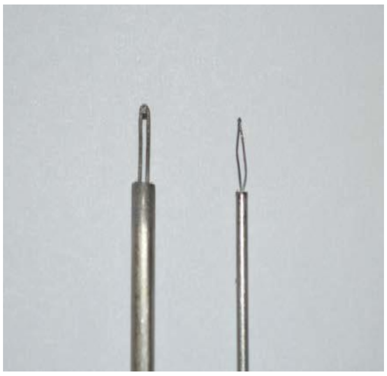

Figure 4. Baseline TC (1/8 inch) and smaller TC (1/16 inch) [20]

3.3. Issues on temperature measurement

Heat energy from convection and radiation are the main issues of heat transferred from fire that are exposed to structures. The convective heat transfer is the dominant heat transfer in liquid and gases, involve the process of conduction (heat diffusion) and advection (heat transfer by bulk fluid). The main factors that influence the convective heat transfer are the temperature differences between the target surface and the surrounding gas, and the velocity of the gas masses in the surrounding area of the exposed surface. The convective heat transfer, q_{conv} can be calculated using Equation 1.

$$q_{conv} = h(T_g - T_s)^n \quad (1)$$

where q_{conv} is convective heat transfer, h is the convective heat transfer coefficient $T_s$is the surface temperature and T_g is the gas temperature outside the boundary layer [2]. The radiation heat transfer is about the exchange of thermal radiation energy between two or more bodies. Thermal radiation is the electromagnetic radiation in the wavelength range of 0.1 to 100 microns. The radiation heat transfer, q_{rad} can be calculated using Equation 2.

$$q_{rad} = \alpha_s q_{inc} - \mathcal{E}_s \sigma T_s^4 \quad (2)$$

where q_{rad} is the net heat absorbed by radiation, q_{inc} is the incident radiation, α_s, $\mathcal{E}_s$, are the surface absorptivity and emissivity, T_s is the absolute temperature and σ is the Stefan's Boltzman constant.

The incident heat radiation on a surface arises from surrounding flames and gas masses as well as other surrounding surfaces [2]. The main issue with thermocouple measuring devices was heat loss due to radiation based on thermocouple bead size, also its sensitivity reduces accuracy as highlighted by Samir and Ryan [9]. Abu Talib *et al.* [5] have earlier reported that the effect of radiation from the thermocouple tip significantly reduces the measured flame temperature, as the radiation losses were corrected, actual peak flame temperature was found to be approximately 800°C above the measured flame temperature. Liquid in-glass thermometer has the disadvantages of inability to measure high temperature, large sensing element, impossibility for continuous or automatic readout, long time constant, awkward dimensions, secular changes and hysteresis as reported by Wise [23]. Resistant temperature detector, thermistor and optical pyrometer are unsuitable to measure high temperature too.

4. Heat Flux Measurement

Heat flux is the rate of heat energy transfer through a given surface, per unit time measured in watt. Heat flux density is the heat rate per unit area measured in watt/metre square [24]. ISO2685 stated that the standard burner should produce 116±10kW/m^2 of heat flux value.

4.1. Method for heat flux measurement

The heat flux can be measured using different approaches such as those reported by Piccini *et al*. [25] that uses Thermographic Phosphors (TFG), Jones [26] and Shultz and Jones [27] uses optical method, and Abu Talib *et. al.* [5] and Ainsworth *et. al.* [28] uses thin film gauge (TFGs) that is more suitable for ISO 2685 standard, which can measure up to 200 kW/m^2, and endure prolonged immersion in a 1900°C flame. Different methods are used in measuring the temperature and heat flux for fire testing. The sample was immersed in flame for 15 minutes to find the material standard and this measurement is to prove the structural integration of the sample. A distance of three inches was used in between the thermocouple and the burner, so that the heat flux was measured according to the ISO 2685 standard [3]. Thin film gauges were used to measure the surface temperature due to its high thermal resistance and negligible influence on the surface flow field. In most of the practical work, radiative heat flux is normally measured with total heat flux meters of Schmidt-Boelter (thermopile) or Gardon (foil) type since they combined heat flux by radiation and convection to a cooled surface, as reported by Pullins [29]. Among the types of heat flux measuring devices are: calorimeter, Gardon gauges and Schmidt-Boelter gauges [1]. The thermocouple or thermometer are installed at the inlet and outlet of the tube of flowing water of calorimeter, which is usually a copper insulated on both sides except on the front side, to measure the inlet and outlet temperature.

Gardon gauge measuring device is in a form of copper-constantan thermocouple, as the gauge was introduced to a constant heat flux, temperature gradients develop in between the centre and at the side of the foil, the thickness of the foil determine the sensitivity of the thermocouple and is developed to produce 10mV as the output signal at the utmost heat flux. It has a water-cooled continues use, radial flow of heat in foil and parabolic temperature distribution. Schmidt Boelter gauge is another type of heat flux measuring device that the temperature difference was measured using a thermopile at the front and back side of aluminium piece, it is also like Gardon gauge, developed to generate output signal of 10mV at the utmost heat flux. It has as an axial flow of heat and a uniform temperature distribution [1]. ISO2685 [3] stated that heat flux from the standard burner must be calibrated using any approved equipment. In the process of calibration at least 180 seconds is required as warm-up time, so that a stable conditions may be obtain before taken the temperature measurements. During the test, water flows in and out of the tube and a thermocouple or thermometer is inserted at the inlet and outlet of the tube of the flowing water. The temperature is recorded of the constant flow of water at every 30 seconds for 180 seconds. This calibration process produces only a single measurement of heat flux averaged over the length of impingement of the flame onto the copper tube. The temperature difference between the inlet and outlet of the water of the surface area of the pipe exposed to heat with the volume flow rate and the density of water gives the heat flux of the flame. It was also found that like in the temperature calibration process, the two standards have different required values of heat flux calibrations. The ISO2685 standard is 116±10 kW/m^2, while AC20-135 106 kW/m^{2}as reported by Samir *et al.* [20].

4.2. Issues on heat flux measurement

Diller [30] reported a number of possible complications that may arises when using a differential heat flux sensor. The main issue is that, when calibration was performed on different ways of heat transfer, it may produce different results. Another issue is that the presence of the heat flux sensor may change the temperature field and heat flux result. Murthy *et al.* [31] reported heat flux calibration of Schmidt Boelter gauge using variable temperature black body (VTBB), whereby the radiating aperture and the apparent emissivity are located at fixed distance from the exit of black body with reference radiometer. The temperature was measured by sensing the radiation from one end of the furnace, which regulate and maintain the temperature within ± 0.1°C by an optical pyrometer.

In the calibration, there is heat loss due to radiation, therefore to ascertain the fraction of total heat flux due to radiation, Pullins [29] developed two different types of heat flux meter for the calibrations: total hemispherical radiometer sensitive to radiation only, and a total heat flux meter (most frequently used) sensitive to both radiant heat transfers and convective heat transfer. Samir *et al.* [20] reported a method of measuring simultaneously the heat flux and a flame temperature within the same distance as shown in Figure 5, whereby the heat flux and flame temperature measuring devices are located at four inches from the burner head.

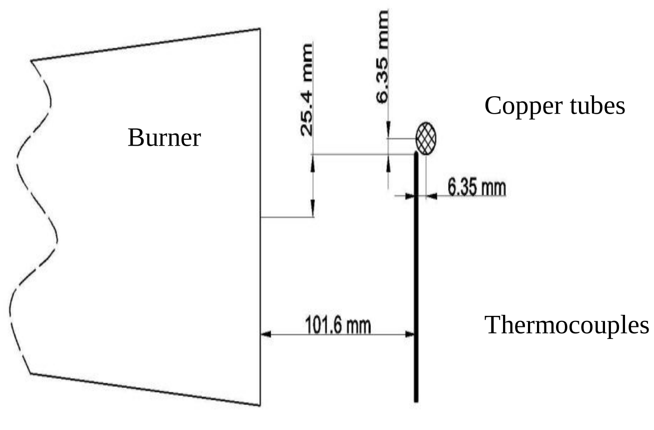

Figure 5. Simultaneous heat flux and temperature calibration for NextGen burner [20]

5. Uncertainty in measurement

There are different errors that can occur during the fire test measurement, which include human error, measurement error, standard error and equipment failure. Human error is one of the errors that brought about the dangerous conditions in the analysis of the results obtained and is prevented by designing different safety instruments in a suitable manner.

Another factor that affect the measurement is error due to measurement, the error is affected by some factors such as those affected by gas velocity over the thermometer, the emissivity and size of the thermometer body, also the radiative heat transfer between the thermometer and its surrounding may influence the temperature reading on thermometer. Abdullah *et al.* [17] reported that, supposing the actual surface temperature was reached by the junction of Type-T thermocouple attached around centre hole of the calibration plate using thermally conductive adhesive, then the general uncertainty in surface temperature measured by the thermionic liquid crystal would be approximated. Most of the general uncertainty found was due to the systematic and random uncertainty during the temperature measurement system. The uncertainty analysis was performed using the Root Sum Square method described by Coleman and Steel [32]. The systematic, random and overall uncertainty was measured to be ±0.38ºC, ±0.39ºC and ±1.08ºC, respectively. Uncertainties that arise on thermocouple temperature measurement and plate thermometer measurement are negligible when compared to other uncertainty that arises as reported by Wickstrom *et al.* [2].

Abu Talib [33] reported the estimate of experimental method of uncertainties using the method described by Moffat [34]. The experiment was performed on flat plate test for the low-temperature analogue burner. The uncertainty level in coefficient of heat and adiabatic wall temperature depends on the initial temperature, gas temperature and surface temperature during calibration process and time. The errors obtained in the experiment were typical errors for initial temperature ±0.5, gas temperature ±0.5 surface temperature ±0.3 and time ±0.04. In the experiment first, second, third and fourth gas temperature steps for uncertainties were evaluated, and the results obtained were analysed and the coefficient of heat and adiabatic wall temperature were deducted. The root sum square (RSS) and maximum error were evaluated for the first, second, third and fourth gas temperature steps for uncertainties. The root sum square can be evaluated using Equation 3.

$$\text{Root sum square, RSS} = \sqrt{x_1^2 + x_2^2 + x_3^2} \tag{3}$$

where x is the uncertainty on the parameters used. The maximum error is the sum of all components error, which is the worst-case error.

Murthy *et al.* [31] reported the uncertainties on heat flux measuring devices whereby some types of uncertainties are evaluated by statistical methods and the other types where evaluated by the other methods. In one of the techniques used in the calibration that is transfer techniques of heat flux sensor, the uncertainties measurement occurs in different ways, but two of these ways are the most important to know. There is uncertainty related to the calibration of the transfer standard radiometer, which is estimated to be 0.6%, and also there is uncertainty associated with calibrating the heat flux sensor with the VTBB, which has the stability of 0.1 K of the used temperature. The uncertainty obtained in this type is very negligible, which corresponds to 0.01 % at 927ºC and 0.004 % at 2500ºC.

6. Conclusion

From the review, it is clear that the temperature and heat flux measuring devices depends fully on the device sensors. Some temperature measuring devices do not have the ability to read high temperature measurement. It was found that, thermocouple of R, S and B types can withstand high temperature. However, the main problem with thermocouple is the bead of the thermocouple and high heat loss due to radiation, which can be reduced using an aspirated thermocouple and a smaller size thermocouple reduces heat loss by radiation. Thermometer can be used to measure the inlet and outlet temperature of heat flux measuring devices since the required temperature in that point is not as high as that recorded in the flame temperature. The sources of errors in measurement are parts of the factors that affect the measurement of flame temperature and heat flux, which can be corrected by designing a suitable safety instrument to avoid error in the measurement. Radiation and convection heat transfer are the main issues that affect the performance measurement of temperature and heat flux due to heat lost that normally encountered during the measurement and it can be reduces by using the right device.

Type R and S thermocouples are good devices used in the calibration and measurement of flame temperature that gives the higher temperature resistance and a low error of 0.1%. Likewise, heat flux calibration and measurement Schmidt Boelter gauge is the good device used in measuring heat flux that regulate and maintain the temperature within ± 0.1°C. Using these devices reduces the error due to measurement and also reduces standard error by the equipment used in calibration. The temperature should be measured using aspirated thermocouple if possible or a small size diameter bead to reduce heat loss by radiation.

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