

NPL REPORT

DEPC-TH 009

Development of Spectral Radiation Thermometry in High Ambient Temperatures

**BUFA ZHANG
ANDREW LEVICK
GORDON EDWARDS**

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JANUARY 2007



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Development of Spectral Radiation Thermometry in High Ambient Temperatures

Bufa Zhang, Andrew Levick and Gordon Edwards

Thermal Measurement Team
Engineering & Process Control Division

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ISSN 1744 - 0289

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

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We gratefully acknowledge the financial support of the UK Department of
Trade and Industry (National Measurement System Policy Unit)

Approved on behalf of the Managing Director, NPL,
by Dr Peter Quested, Knowledge Leader, Thermal Measurement Team

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EXECUTIVE SUMMARY

This project aims to develop a novel technique for accurately measuring temperature of targets in environments where strong background radiation affects temperature measurement using pyrometers. This difficulty of background radiation exists in many industrial applications such as steel billet reheating in furnace, blades in turbine engine etc.

Radiation Thermometry in High Ambient Temperatures (RTHAT) uses a subtraction method to minimise the effect of background radiation in the target temperature measurement, in which two pyrometers are utilized: one recording the target radiation and the other detecting the background radiation. A correction can be made to minimise the effect of reflected radiation in the target signal by correlating two measured signals and taking advantages of the temporal or spectral signatures in the background radiation if available.

In the previous Thermal Programme, a temporal RTHAT apparatus has been developed for accurate temperature measurement in the presences of reflected background radiation. The temporal RTHAT apparatus exploits temporal variations in background radiation and it is most suitable for situations where the background radiation varies significantly with time. The technique has been evaluated with experiments on a platinum and an oxidised Inconel alloy with a bulb of sinusoidally-modulated power for background radiation source. It is regarded to be a temperature measurement technique suitable for applications such as lamp-heated Rapid Thermal Processing (RTP) of silicon wafers for which the technique was initially developed.

For other industrial situations where the background temperature and its radiation are stationary and different from those of the target whose temperature is to be determined, a spectral RTHAT technique is investigated in this project. The principle of the spectral RTHAT technique under development is based on the Planck's law: the radiation spectrum emitted by an ideal blackbody depends on wavelength and its temperature. If the target temperature is different from that of background, it is possible to accurately determine the target temperature by minimising the effect of background radiation via exploiting the difference in radiation spectrum between them due to differences in their temperatures and emissivity spectra.

There are three basic scenarios for spectral RTHAT: -

- (i) where the background is smooth Planckian due to emission from solid objects;
- (ii) where the background is spectrally structured due to emission from for example combustion gases;
- (iii) there may be a mixture of these components, *e.g.* in a gas turbine engine, that is closer to practical situations.

Various radiation thermometry techniques have been reviewed in this project. Theoretical analysis has been carried out and computer modelling using Matlab has been developed to investigate the effect of reflected background radiation on the temperature measurement of a target. Radiation signal from a disc target inside a tube

furnace has been studied where temperature gradients along the furnace wall were considered with use of the configuration factor technique. The result shows that high-accuracy temperature measurement of the target is possible provided that a reference signal representing background radiation is measured from a suitable location on the furnace wall. The sensitivity of the proposed RTHAT technique also has been investigated.

A portable spectral RTHAT apparatus has been built, consisting of a laptop PC, an optical detection head and an InGaAs array spectrometer. It has several advantages including:

- (i) passive technique;
- (ii) low cost;
- (iii) without the need for a prior knowledge of the target emissivity and;
- (iv) no signal saturation difficulty for high temperature measurement.

The InGaAs spectrometer has many features including the compact size making it suitable for use for in-situ measurements, high sensitivity and fine spectral resolution (*i.e.* 256 detector pixels) over a wide wavelength range (*i.e.* 0.9-1.7 μm).

The spectral RTHAT apparatus has been tested in three experiments with:

- (i) a bulb for background radiation source;
- (ii) a high temperature facility and;
- (iii) a purpose-designed Inconel target heated inside a sodium heat pipe.

In the last experiment, the surface temperature measured by the RTHAT apparatus has been compared with those by inserted thermocouples and a good agreement between them was found.

The new spectral RTHAT technique developed in this project is based on conventional multi-wavelength pyrometry techniques for temperature measurement, with several new features including:

- (i) use of a spectrometer for measuring radiation over a wide and continuous range of wavelength;
- (ii) new data analysis method employed for more accurate temperature determination;
- (iii) two detection probes used to effectively minimise the effect of background radiation.

The spectral RTHAT technique has significant advantages over the conventional pyrometry techniques. In the conventional multi-wavelength pyrometry techniques, in order to overcome the difficulty of unknown target emissivity, radiation signals from the target are measured at m different wavelengths. In a general case, it needs to use a polynomial function of $(m-1)$ th order to exactly represent the unknown target emissivity at m measurement wavelengths. However, it is usually impossible to work out $m+1$ unknowns (*i.e.* m in the polynomial plus the unknown target temperature) from m measurements. To make the problem solvable, as a compromise, the target emissivity is approximated by a $(m-2)$ th order polynomial function. As a result, the performance of multi-wavelength pyrometry highly relies on the level of agreement of the polynomial approximation to the true target emissivity. Also the polynomial data fitting for m unknowns from m measurements is *perfect* without any fitting residuals,

and thus the quality of data fitting cannot be examined. But however, in many cases, the disagreement between them can cause large errors in the target temperature measurement. This is a long-standing issue for multi-wavelength pyrometry techniques.

In the spectral RTHAT technique investigated this work, radiation signals are measured at 256 wavelengths with equal intervals over a wavelength range of 0.9-1.7 μm . It is proposed to assume a linear (or constant) wavelength dependence of target emissivity (it is usually a good assumption for most condensed materials at high temperatures). A few measurements at consecutive wavelengths over a narrow band (*e.g.* 0.05 μm bandwidth) can be used in data fitting to compute the emissivity function and temperature of the target. Since the number (*i.e.* 16 for 0.05 μm bandwidth) of measurements used here is larger than the unknowns (*i.e.* 3 for linear wavelength dependence of target emissivity assumption) in the data fitting, residuals between the fitted values and those measured are expected and can be used to compute a chi-squares value to assess the quality of data fitting. Furthermore, this data fitting can be applied to all measurements by scanning the small wavelength band over the whole measurement wavelength range to obtain a set of target temperature values, together with a set of chi-squares values. By finding the minimum chi-squares value, it is possible to find the wavelength band where the target emissivity is mostly close to the assumed linear dependence on wavelength. In this way, it is expected that the temperature measurement using the RTHAT technique could be much more accurate than using conventional multi-wavelength pyrometry techniques.

In the future, in order to make the RTHAT technique work in industrial applications, further effort is needed in the following areas:

- (i) improvements to computer programming for efficiently and rapidly searching optimal target temperature;
- (ii) further study in data analysis for more accurate temperature determination with improved measurement uncertainty; and
- (iii) it can be considered to scan the reference detector to measure radiation over whole background surface to represent the true background contribution in the target signal, when the background radiation is non-uniform.

1 Background

Radiation pyrometry is a well-established non-contact thermometry technique used in a wide range of industrial processes. A radiation pyrometer detects thermal radiation emitted from the target over a range (which could be a narrow band) of wavelengths, and infers the temperature via the Planck radiation law and target emissivity. Radiation pyrometry is an accurate method of surface temperature measurement because of the high sensitivity of the thermal radiance to changes in temperature. It is relatively simple, cheap and robust.

For instance, the brightness (single-colour) pyrometer determines the target temperature using the radiation signals measured over a narrow band of wavelength from the target surface. Therefore the target emissivity needs to be known and stable prior to a measurement.

In practical applications, the main difficulties of the radiation pyrometry are the requirement for prior knowledge of the target emissivity and signal contamination due to reflected radiation from other sources. Those problems need to be addressed in many applications, such as steel reheating in a furnace, oven industry, material processing where strong background radiation exists that can cause large errors in target temperature measurement.

Several types of radiation thermometers have been developed aiming to overcome the emissivity difficulty. Emissivity is a surface property of solid and sensitive to many factors such as contents, surface roughness and its processing history. Furthermore, target emissivity may change during a measurement particularly at high temperatures.

Ratio (two-colour) pyrometer doesn't require the knowledge of target emissivity by assuming greybody target (*i.e.* emissivity is wavelength independent) and measuring its radiation signals at two different wavelengths. In this way, the parameter of emissivity in target signals is cancelled in the temperature calculation. However, the greybody assumption is not valid for many applications where target emissivity often changes with wavelength and the technique may produce even larger errors in temperature measurement than those by brightness (single λ) pyrometers.

Other multi-wavelength pyrometers using more than two wavelengths were also attempted to resolve this emissivity issue. But their success was very limited because the extrapolation of approximation emissivity polynomial is highly sensitive to measurement noises and may cause wildly uncontrolled divergence in the temperature calculation.

Therefore, to measure the temperature of a target whose emissivity is unknown, the pyrometer needs to be emissivity independent.

Furthermore, in many practical applications of pyrometry temperature measurement, the radiation signal emitted by a target also can be seriously contaminated by radiation from the background, which can cause large errors in temperature measurement. To overcome this difficulty, a ripple technique has been successfully

developed by DeWitt *et al* [1997] and applied to the temperature measurement of silicon wafers in the lamp heating process.

At NPL, two techniques of radiation thermometry in high ambient temperatures (RTHAT) have been investigated that exploit respectively the temporal and spectral features in the background radiation to correct for its effect on target temperature measurement. RTHAT methods employ a subtraction technique exploiting different features in the background and target radiation in either time or wavelength domain. Using these features, the reflected background radiation can be distinguished and corrected for in the measured target signal.

During an RTHAT measurement, radiation signals from a target surface (S_0) and its background (S_b) are measured separately in either time or wavelength space. When the background radiation is assumed uniform and the target surface diffuse, a theoretical model can be developed to calculate the radiation signal S_{Model} including the contribution of the reflected background radiation at target surface. Using the least-square curve-fitting technique, the target temperature (T) and emissivity (ε) can be computed by minimising χ^2 of data fitting residuals

$$\chi^2 = \sum_{i=1}^{i=N} (S_0(i) - S_{Model}(i))^2 \quad (1.1)$$

where i is the sequence of N total data in either time or wavelength space.

A temporal RTHAT apparatus has been built in the last Thermal Programme and it is suitable for temperature measurement where a target is at a stable temperature while there are significant fluctuation components in its background radiation.

In this work, a spectral RTHAT technique is investigated, which exploits the spectral differences between radiation emitted by a target and that from its background. The new measurement apparatus is developed with use of a portable spectrometer that employs the latest integrated detector-array technology.

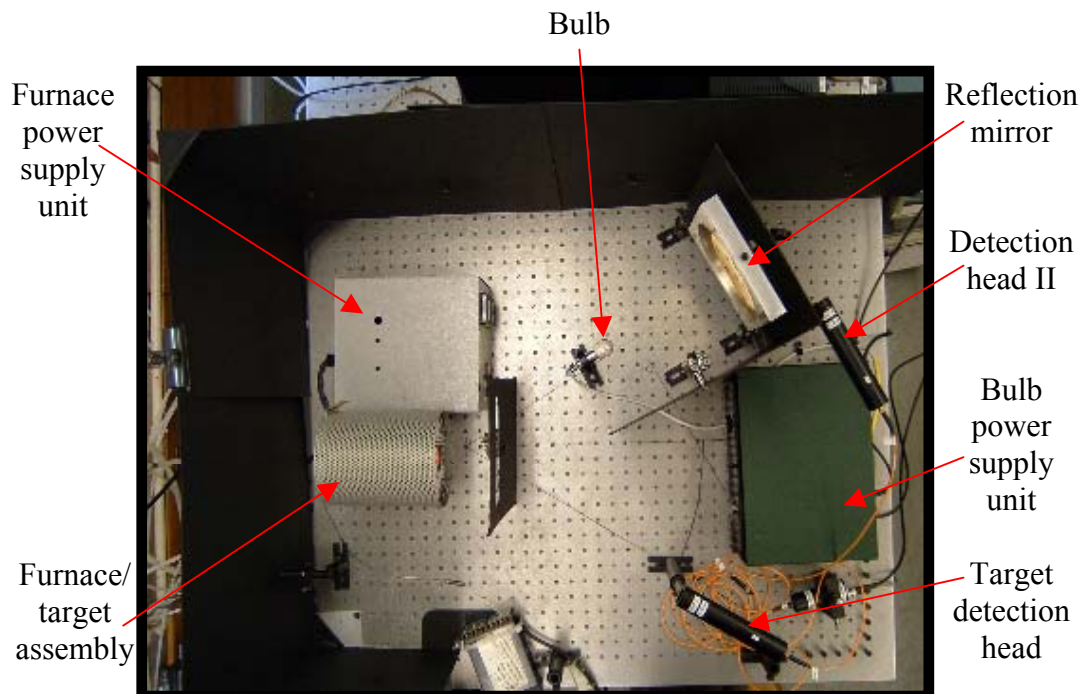
This report describes the development of the spectral RTHAT technique including its principle, computer modelling, construction of apparatus and preliminary experimental results obtained in the laboratory.

1.1 Temporal RTHAT technique

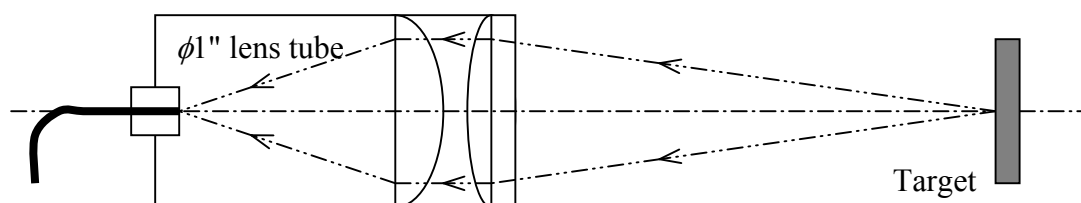
As shown in Figure 1.1, the temporal RTHAT apparatus developed at NPL employs a direct background subtraction technique (also called generalised ripple technique), for measuring surface temperature of samples with strong background radiation in presence.

In the apparatus, a radiation pyrometer (detector 1) collects and detects thermal radiation from the target surface over a narrow band of wavelengths while a second pyrometer (detector 2) is used to monitor the background radiation. In both pyrometers, collected radiation is delivered via optical fibres and focused by using an

aspheric lens (f11 mm, NA = 0.25, A/R coated for 1.55 μm , C220TM-C) to an amplified InGaAs photodiode detectors ($\phi 1$ mm, PDA400-EC) for signal detection. The detection wavelength of 1.55 μm is chosen for high sensitivity of the detector and low noise radiation emitted by combustion gases.



(a)



(b)

Figure 1.1 (a) photo of the NPL temporal RTHAT system and; (b) structure diagram of optical detection head consisting of two lens tubes (2" $\times$ $\phi 1$ " SM1L20 and 3" $\times$ $\phi 1$ " SM1L30 lens tubes) and a plano-convex lens (A/R coated 1050-1620 nm, f400 mm, $\phi 25.4$ mm, LA1172-C) for collecting and a plano-convex lens (A/R coated 1050-1620 nm, f100 mm, $\phi 25.4$ mm, LA1509-C) for delivering radiation to a two metre SMA patched fibre cable (FG-200-LCR) with a SMA adapter (SM1SMA), all components supplied by Thorlabs, Ltd. UK.

If the radiation emitted by the target surface is stationary while background radiation exhibits significant fluctuations, the direct and reflected radiations received from the target surface can be distinguished and separated using a computer programme. In this way, the contribution of the reflected background radiation in the signal measured by detector 1 can be corrected for by correlating two signals. Then both target temperature and emissivity can be determined using Planck's law. (For details of the technique, see a previous NPL report by Gavin Sutton, 2003).

In summary, in the temporal RTHAT technique, the following assumptions are used:

- The sample emissivity is known or,
- The sample emissivity can be determined from the reflectivity measurement when the background radiation is spatially uniform to the sample surface,
- The radiation emitted from the sample is stationary while the background radiation possesses significant fluctuations in time enabling the direct and reflected radiations to be distinguished.

The main features of apparatus include:

- Low cost – mainly two passive radiation pyrometers
- Simple technology
- Completely non-invasive
- Fast – potential measurement speed on millisecond scale
- Applicable to a wide range of applications
- Use temporal or noise signature in the background radiance
- Large signals and therefore low random uncertainty for measurements at temperatures above 500 °C.
- Safe – no high power lasers involved

The NPL RTHAT apparatus has been tested successfully with measurements on oxidised Inconel steel and polished platinum representing samples of high and low emissivity respectively. A light bulb is used to provide a sinusoidally modulated background radiation to the sample surface. The results show that the background radiation can be corrected from the sample signal and the RTHAT thermometer can measure sample surface temperature with an accuracy of a few degrees for measurement temperatures between 600 °C and 1000 °C assuming the sample emissivity is known.

The temporal RTHAT apparatus exploits temporal variations in background radiation and therefore is most suitable for situations where the background radiation varies significantly with time.

1.2 Spectral RTHAT technique

To accurately measure temperature when the background radiation is stationary, the technique under development - namely the spectral RTHAT, involves separate spectral measurements of the background and target radiances. Similarly a least

squares analysis is then utilised to obtain the surface temperature and emissivity of the target. The technique relies on the extra information provided by different features in the background radiation spectrum that can be correlated with the reflected radiation from the target.

In this study, the target was assumed small in comparison with the background, and thus the multiple reflections of thermal radiation between them can be neglected. It was further assumed that the target surface to be measured was surrounded by a hemisphere emitting uniform radiation. This would be the case for a diffuse background with uniform emissivity and temperature. Then the detected target signal can be represented by

$$S_0(\lambda_i) = \varepsilon L(\lambda_i, T_s) + r S_b(\lambda_i, T_b) \quad i = 1, 2, \dots, N \quad (1.2)$$

where T_s and ε are the temperature and emissivity of the target, λ the wavelength, T_b the background temperature and r the coupling factor of reflected background radiation which is dependent on the reflectivity of target and the configuration factor between the target surface and the background geometry. $L(\lambda, T)$ is the Planckian function of temperature and wavelength for spectral distribution of radiation from an ideal blackbody. S_b is the radiation component from background. The first part on the right-hand side of the equation is the contribution from the radiation emitted by the target surface and the second by the reflected background radiation.

When the temperatures of a target and its background are different, according to Planck's law, the spectra of radiation emitted by them are different. Thus, using a correlation technique in the wavelength domain similar to that in the time domain discussed in Section 1.1, the reflected background radiation can be corrected for from the detected target signal. Details of the technique will be discussed in the next section.

2 Spectral RTHAT pyrometry

When the background radiation is stationary, it does not have a “ripple” component for the temporal RTHAT technique to use. Instead the differences in the radiation spectra from the target and from the background can be exploited to distinguish and separate them, since the radiation distribution varies with temperature according to Planck's law. Therefore the spectral RTHAT is more suitable for temperature measurement when the temperature difference is large between the target and its background as in many steel industry applications, such as steel billets in reheating furnace. The uncertainty in temperature measurement using the spectral RTHAT can be improved if other spectral characteristics can be used in either the target emissivity or the background radiation, for example, emission lines of gases in a combustion engine.

In this work, both the target and its background are assumed in a stationary condition, *i.e.* their temperatures are considered constant, the target surface is diffuse and the background radiation is uniform. Then the measured signal can be divided into two

parts corresponding to contributions from the radiation emitted by the target and the reflected background radiation as follow.

$$S(\lambda) = B \left[\frac{\varepsilon_s}{\lambda^5} \frac{1}{e^{\frac{C_2}{\lambda T_s}} - 1} + (1 - \varepsilon_s) \frac{A_b}{\lambda^5} \frac{1}{e^{\frac{C_2}{\lambda T_b}} - 1} \right] \quad (2.1)$$

where:

C_2 : = 14388 $\mu\text{m}\cdot\text{K}$, the second radiation constant

ε_s : target emissivity

T_s : target temperature in Kelvin

A_b : coupling coefficient dependent on background emissivity and geometric factors etc.

ε_b : background emissivity

T_b : background temperature in Kelvin

B : instrumental factor that can be determined via calibrating the system against a reference radiation source.

2.1 Radiation signal

It is assumed that the target is small in comparison with the background, and thus the effect of multiple reflections of thermal radiation between them can be considered to be negligibly small.

Both ε_s and A_b can be functions of wavelength, temperature and viewing angle. In this study, wavelengths (λ) and temperatures (T) investigated are limited up to 1.7 μm and 1900 K respectively. Thus, $\lambda T \ll C_2$ is satisfied and, the above equation may be simplified using Wien's law

$$S(\lambda) = B \left[\frac{\varepsilon_s}{\lambda^5} e^{-\frac{C_2}{\lambda T_s}} + (1 - \varepsilon_s) \frac{A_b}{\lambda^5} e^{-\frac{C_2}{\lambda T_b}} \right] \quad (2.2)$$

Equation (2.2) will be used mostly in this study while Equation (2.1) is used where $\lambda T \ll C_2$ is not satisfied. Figure 2.1 demonstrates a typical signal calculation using Equation (2.2). The calculation is performed from 0.5 to 4 μm for a target at temperature $T_s = 1000$ K and having an emissivity $\varepsilon_s = 0.4$ with and without reflected background radiation at $T_b = 1100$ K and coupling factor, A_b varying from 0.1 to 1. The graphs show that the radiation signal from the target surface to be measured can be dramatically affected by the reflected background radiation.

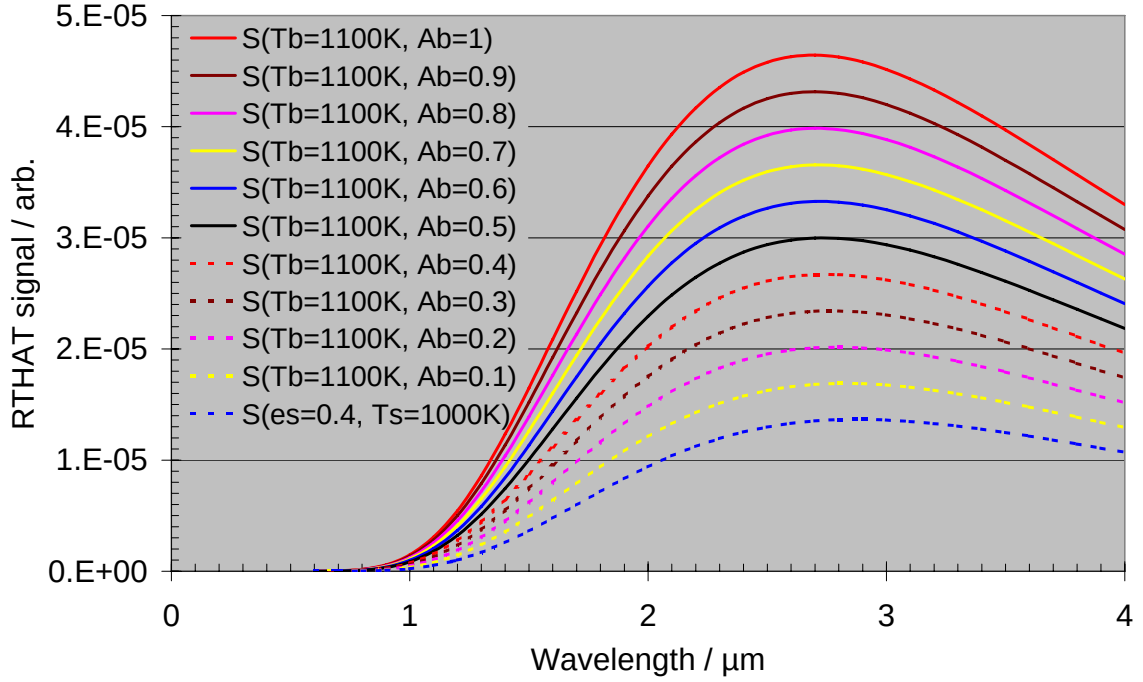


Figure 2.1 RTHAT signal calculation from 0.5 to 4 μm , for a target at $T_s = 1000$ K and having emissivity $\varepsilon_s = 0.4$ with reflected background radiation at $T_b = 1100$ K and coupling factor A_b varying from 1 to 0.1 (curves from top to lower). There is no reflected background radiation in the lowest signal curve.

For data reduction, Equation (2.2) can be re-organised to give:

$$\ln(\lambda^5 S) = \ln(B) + \ln(\varepsilon_s) - \frac{C_2}{\lambda T_s} + \ln \left[1 + A_b \frac{1 - \varepsilon_s}{\varepsilon_s} e^{\frac{C_2}{\lambda} \left(\frac{1}{T_s} - \frac{1}{T_b} \right)} \right] \quad (2.3)$$

When there is no background radiation, the above equation reduces to

$$\ln(\lambda^5 S) = \ln(B) + \ln(\varepsilon_s) - \frac{C_2}{\lambda T_s} \quad (2.4)$$

Equation (2.4) is widely utilised in data analysis of two-colour pyrometry for temperature measurement. It shows a linear dependence of $\ln(\lambda^5 S)$ signal on λ^{-1} , if the target is a greybody (*i.e.* its emissivity is wavelength independent). Then the target temperature (T_s) can be determined from the gradient of the $\ln(\lambda^5 S)$ versus λ^{-1} curve.

For the multi-wavelength pyrometry that measures radiance at more than two wavelengths, Equation (2.4) is modified to

$$\lambda \ln(\lambda^5 S) = \lambda \ln(B) + \sum_{n=0}^{m-2} c_n \lambda^n - \frac{C_2}{T_S} \quad (2.5)$$

where m is the number of wavelengths at that radiances are measured, c_n the coefficients of polynomial and $\lambda \ln(\varepsilon_S)$ in Equation (2.4) is replaced by a $(m-2)$ th order polynomial defined by

$$\lambda \ln(\varepsilon_S) = \sum_{n=0}^{m-2} c_n \lambda^n \quad (2.6)$$

Now there are m unknown parameters (*i.e.* c_0 to c_{m-2} plus T_S) in Equation (2.5) that can be determined from the m radiation measurements. The target temperature can be determined by extrapolating the fitted curve to $\lambda = 0$, (*i.e.* by setting $\lambda = 0$ in Equation (2.5)) to give

$$T_S = \frac{C_2}{c_0} \quad (2.7)$$

For demonstration, radiation signals were calculated in Figure 2.2, over a wavenumber (λ^{-1}) range from 0.6 to 1.1 μm^{-1} (corresponding to a wavelength range about from 0.9 to 1.7 μm of an InGaAs spectrometer to be used later), for a target at temperature $T_S = 1073$ K and having an emissivity $\varepsilon_S = 0.7$ respectively with and without contamination of background radiation at $T_b = 1173$ or 1273 K and with a coupling factor $A_b = 0.63$. For the signal curve with no background noise, the target temperature can be calculated from the gradient of the curve. For the other two cases, the calculation of correlation coefficient R^2 between signal data and its linear regression fitting measures the degree of linearity of the contaminated signal curves. For the investigated two cases in Figure 2.2, although their magnitudes and gradients have changed significantly because of the reflected radiation, the changes of R^2 from 1 in the linear data fitting of the signal curves are too small to reflect the signal distortions. Therefore the independent direct measurement of background radiation is needed to minimise its effect on target temperature measurement.

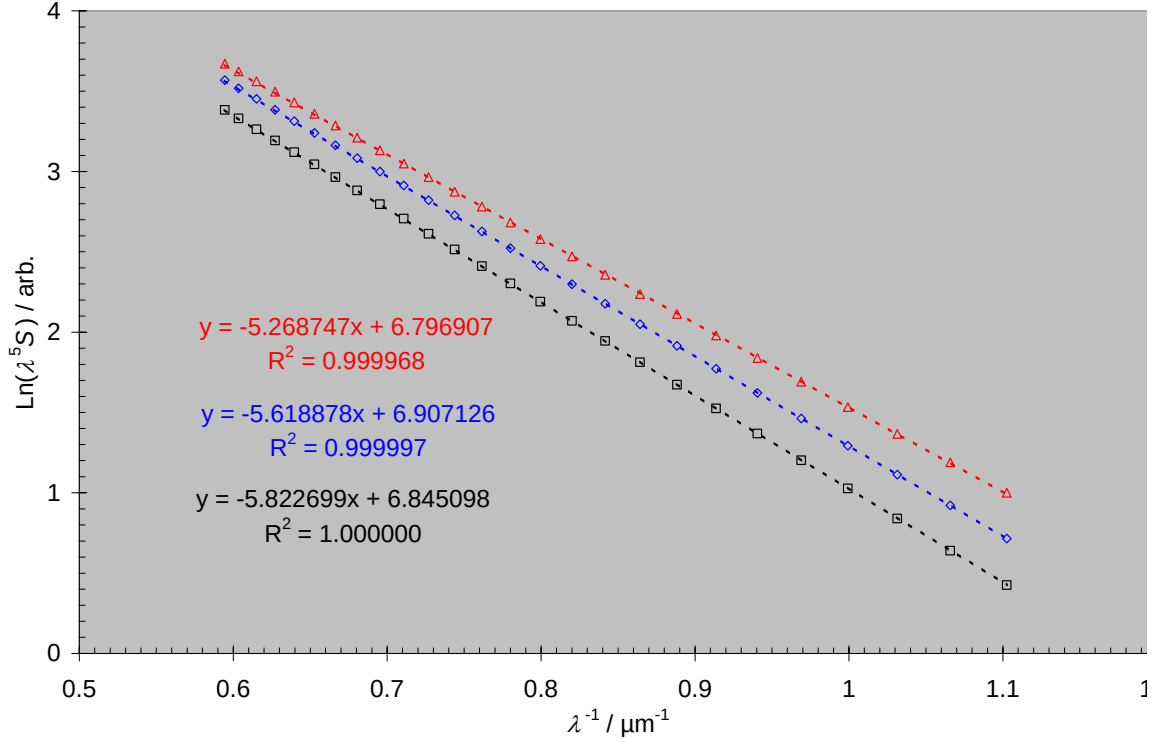


Figure 2.2 Linear data fitting of radiation signals from a target at $T_S = 1073$ K temperature and having an emissivity $\varepsilon_S = 0.7$, with and without the reflected background radiation. Calculated data points and their linearly fitted lines, from lower to upper, correspond to respectively signals not affected by background radiation, and those affected by background radiation with $A_b = 0.63$ and $T_b = 1173$ and 1273 K.

2.2 Error analysis for temperature measurement

An error analysis has been carried out to study the effect of target emissivity accuracy and background radiation contamination on the temperature measurement using conventional radiation pyrometers. The true target temperature was set $T_S = 1000$ K for calculating simulation radiation signals with effect of reflected background radiation. The target temperature is then determined from the signals using the single- and double- colour pyrometry techniques and then their accuracy is studied.

Single-colour pyrometry: the error analysis is carried out for temperature measurement using a single-colour pyrometer with a $\lambda = 0.8$ μm working wavelength. The radiation emitted by the target is calculated with $T_S = 1000$ K and the sample emissivity varying from $\varepsilon_S = 0.1$ to $\varepsilon_S = 1.0$ with 0.1 interval steps. The reflected background radiation is calculated with $T_b = 1100$ K and $A_b = 0.5$. $\varepsilon_{\text{pyro}} = 0.4$ is set in the pyrometer as a typical medium emissivity value for solid materials in the analysis.

Figure 2.3 shows the differences as a function of target emissivity, between the true target temperature ($T_S = 1000$ K) and those “measured” by the pyrometer. When the background temperature is relatively low (*e.g.* $T_b = 700$ K), the effect of background

radiation is small and the temperature error is mainly caused by the difference between the emissivity set in the pyrometer and the true target emissivity. The effect of background radiation increases with its temperature and it becomes dominant when the background temperature is higher than that of the target even when the target emissivity is set properly to $\varepsilon_S = \varepsilon_{Pyro} = 0.4$. It shows that the temperature error caused by the background radiation can be large ($\Delta T > 300$ K) when the reflected background radiation becomes dominant in the calculation. At $\varepsilon_S = 1.0$ where there is no background radiation reflected at the sample surface, thus the temperature error is caused by only the error in the emissivity setting ($\varepsilon_{Pyro} = 0.4$) of the pyrometer, and therefore is independent of the furnace temperature.

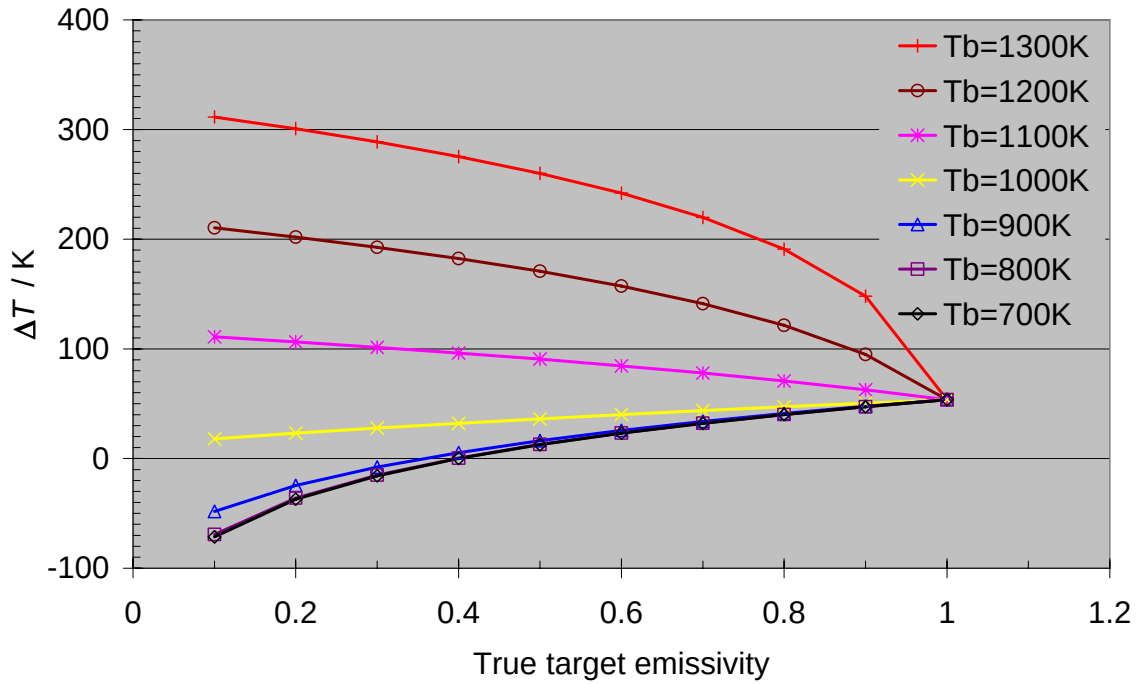


Figure 2.3 Error in temperature measurement versus target emissivity, due to reflected background radiation and mismatch of emissivity setting in a single-colour pyrometer with $\lambda = 0.8 \mu\text{m}$, $T_S = 1000$ K, $\varepsilon_{Pyro} = 0.4$ and $A_b = 0.5$.

Similar analysis is performed in Figure 2.4 for the effect of background radiation with different values of coupling factor A_b varying from 0.1 to 1. The results show that the effect increases with the background temperature (T_b) and the coupling factor.

Double-colour pyrometry: the error analysis is also carried out for temperature measurement using a double-colour pyrometer with $\lambda_1 = 0.7 \mu\text{m}$ and $\lambda_2 = 0.9 \mu\text{m}$ as working wavelengths. The effect of target emissivity on temperature measurement is investigated in Figure 2.5, with parameters $A_b = 0.5$, $T_S = 1000$ K and the sample emissivity varying from $\varepsilon_S = 0.1$ to $\varepsilon_S = 1.0$ with 0.1 interval steps. In the application of double-colour pyrometry, the target is assumed to be a greybody with an emissivity

independent of wavelength. Therefore no knowledge is required for target emissivity for temperature measurement using a double-colour pyrometer.

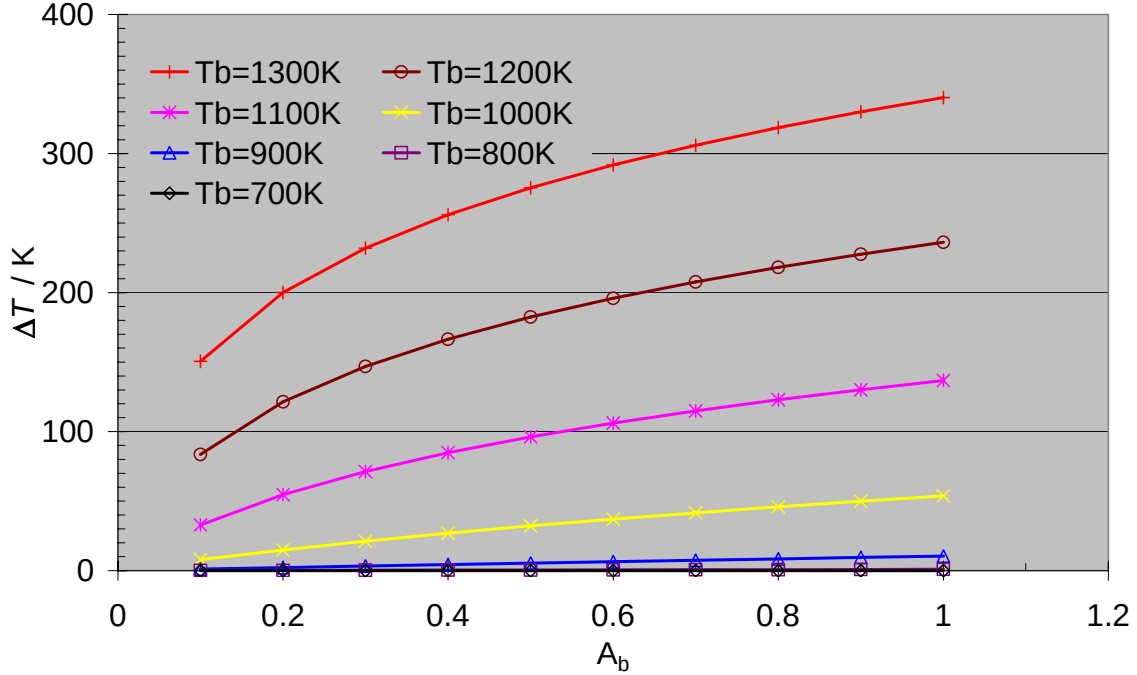


Figure 2.4 Error in temperature measurement versus A_b caused by background radiation using a single-colour Pyrometer with $\lambda = 0.8 \mu\text{m}$, $T_S = 1000 \text{ K}$, $\varepsilon_S = \varepsilon_{\text{Pyro}} = 0.4$.

Figure 2.5 shows the differences between the true target temperature ($T_S = 1000 \text{ K}$) and those “measured” by the pyrometer. Most of them are smaller than those measured by the single-colour pyrometer presented in Figure 2.3. When the background temperature is relatively low (*e.g.* $T_b = 700 \text{ K}$), the effect of background radiation is small. The effect of background radiation increases with its temperature and becomes large when the background temperature is higher than that of the target. It is worth pointing out that (i) the dependence of temperature error on target emissivity is relatively weak which is expected for the double-colour pyrometry technique; and (ii) the temperature error monotonically decreases with target emissivity because the contribution to the signal from background radiation decreases with increasing target emissivity according to Equation (2.1).

Also shown in Figure 2.6 is the effect of background radiation on target temperature measurement with respect to the furnace temperature (T_b). It shows that the error increases with the furnace temperature and the coupling factor, and is approaching “saturated” when the coupling factor (A_b) is larger than 0.4 in this investigation. This saturation is caused by the dominance of the reflected background radiation in the “detected” radiance, and the “saturated” error is the temperature difference between the background and target.

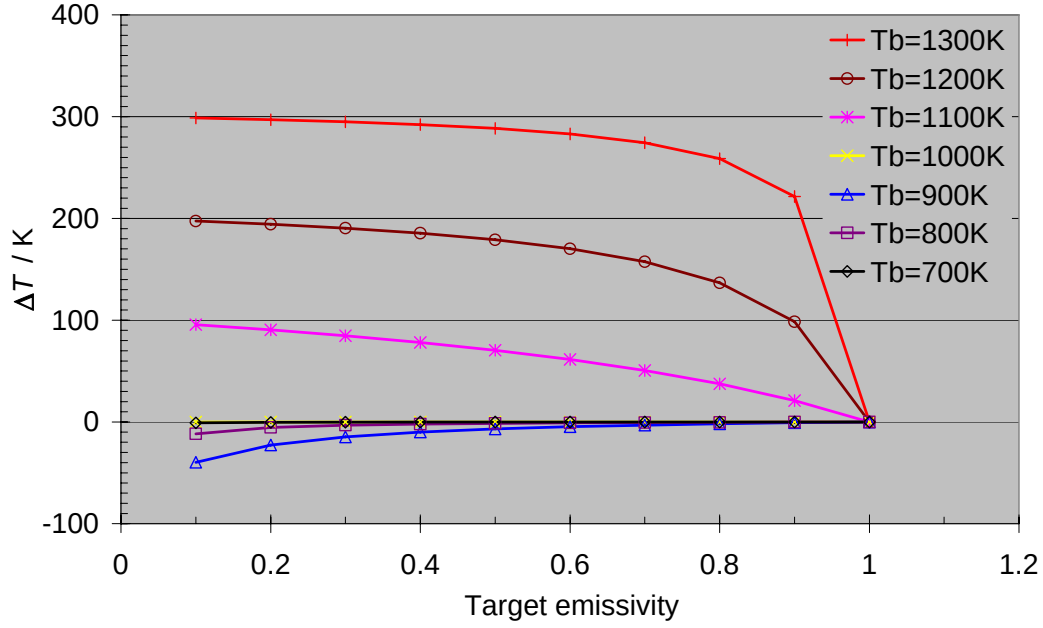


Figure 2.5 Error in temperature measurement versus target emissivity caused by the reflected background radiation using a double-colour pyrometer with $\lambda_1 = 0.7 \mu\text{m}$, $\lambda_2 = 0.9 \mu\text{m}$, $T_S = 1000 \text{ K}$ and $A_b = 0.5$.

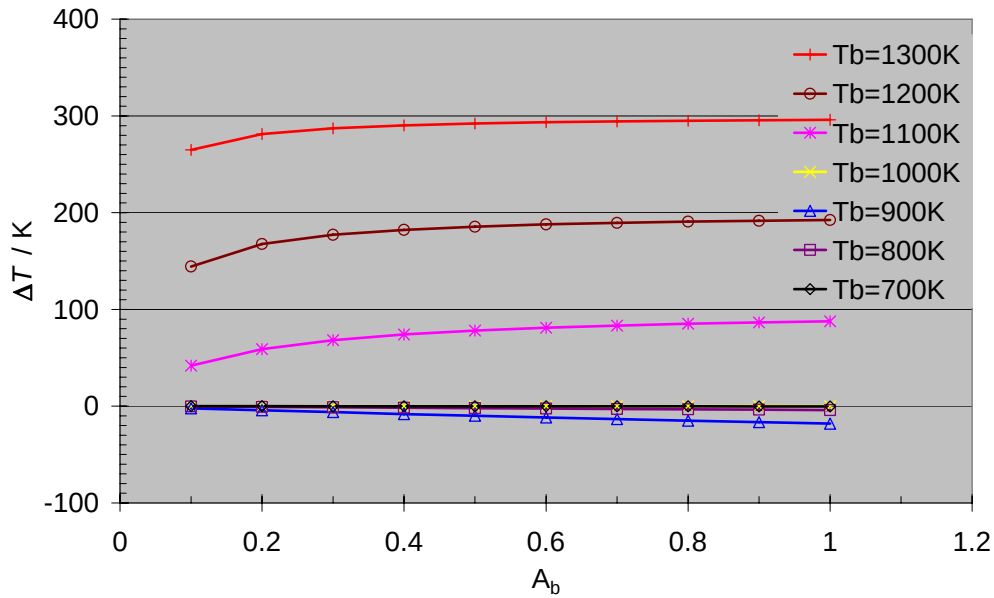


Figure 2.6 Error in temperature measurement versus A_b caused by the reflected background radiation using a double-colour pyrometer with $\lambda_1 = 0.7 \mu\text{m}$, $\lambda_2 = 0.9 \mu\text{m}$, $T_S = 1000 \text{ K}$ and $\varepsilon_S = 0.4$.

3 RTHAT computer modelling

To apply the spectral RTHAT technique in industrial applications, computer models have been developed to estimate the effect of background radiation on the temperature measurement of targets in hostile environments. The sensitivity of the technique has also been analysed numerically with some typical examples.

3.1 Modelling using configuration factor technique

To accurately study the effect of reflected background radiation, determining radiation exchange between surface areas of target and furnace wall is needed. The configuration factor technique is employed for calculating this radiation exchange in this study, assuming that both the target and furnace wall have diffuse surfaces for radiation. This technique is particularly useful when the background temperature, $T_F(x)$, is non-uniform.

For simplicity and clarity, a system of a disc target inside a tube furnace, shown in Figure 3.1, is investigated. The configuration factor between a narrow ring element on the furnace wall and a disc sample face can be derived to give [Siegel and Howell, 1992]

$$F_{dA_F-S} = \frac{1}{2} \frac{x}{r_F} \left[\frac{1 + \left(\frac{r_S}{r_F}\right)^2 + \left(\frac{x}{r_F}\right)^2}{\sqrt{\left(1 + \left(\frac{r_S}{r_F}\right)^2 + \left(\frac{x}{r_F}\right)^2\right)^2 - 4\left(\frac{r_S}{r_F}\right)^2}} - 1 \right] \quad (3.1)$$

where

- r_S : radius of disc sample;
- r_F : inner radius of tube furnace;
- x : distance from sample surface to ring element on the furnace wall in the axial direction.
- dA_F : $= 2\pi r_F dx$ area of narrow ring element with a width dx .

Calculations of Equation (3.1) have been performed under various conditions and the results are presented in Figure 3.2. It shows that the configuration factor strongly depends the position of the ring element on the furnace wall, furnace radius and target radius. The peak position of configuration factor is where the furnace wall radiation affects sample signal most significantly and therefore is the optimal position for taking the reference signal of background radiation. The calculation shows that the peak position shifts from $x/r_F = 0.575$ when $r_S/r_F = 0.01$ to $x/r_F = 0.563, 0.482, 0.2$ and 0 when $r_S/r_F = 0.2, 0.5, 0.9$ and 1 respectively. The full width of half maximum (FWHM) of the peak also decreases from 1.21 to 1.20 and 1.13 correspondingly. The calculation demonstrates that, for a target whose radius is smaller than half that of the

furnace tube, the optimal position on the furnace wall for taking the reference background radiation signal is at a distance of about $x/r_F = 0.57$ from the target.

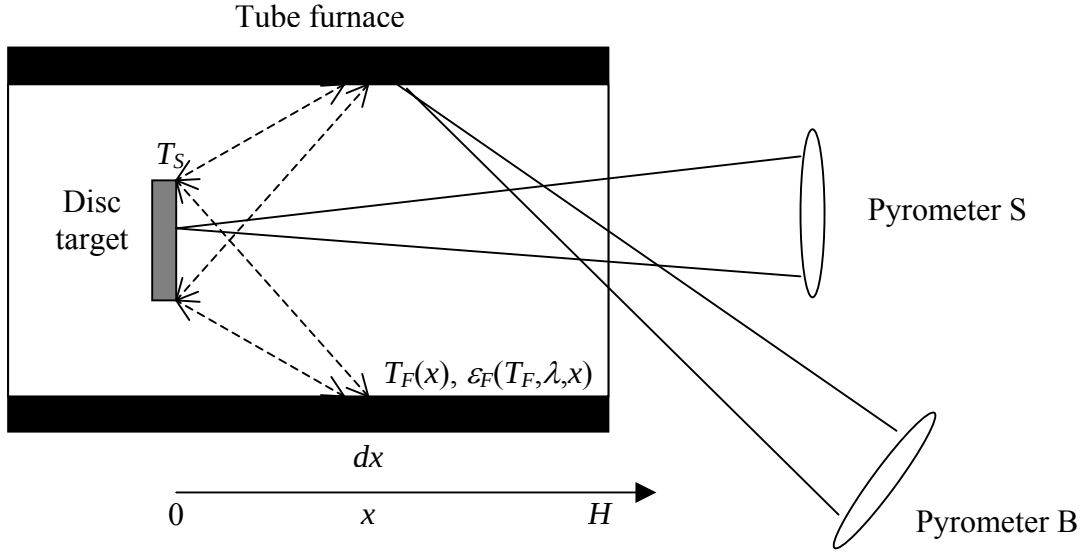


Figure 3.1 Principle diagram of a disc target co-axis located inside a tube furnace for the analysis of the radiation configuration factor between them. The pyrometers S and B measure radiance from the target surface and a reference point on the furnace wall respectively.

Since the surface of the target is assumed small in comparison with that of the furnace wall, the multiple radiation reflection components between them are small and thus are not considered in this study. If the temperature at the furnace wall is assumed symmetrical to its central axis, the radiation from the furnace wall impinging at the sample surface can be calculated by

$$S_{refl}(\lambda) = \int_{x=0}^{x=H} W(\lambda, x) F_{dA_F-S} dA_F \quad (3.2)$$

where

- T_S : temperature of sample;
- T_F : temperature of furnace wall;
- ε_F : emissivity of furnace wall that can be angle and wavelength dependent;
- $W(\lambda, x)$: spectral radiation distribution on the furnace wall, including reflected components from other parts of furnace wall.
- H : distance from the end of furnace tube to the sample surface to be measured

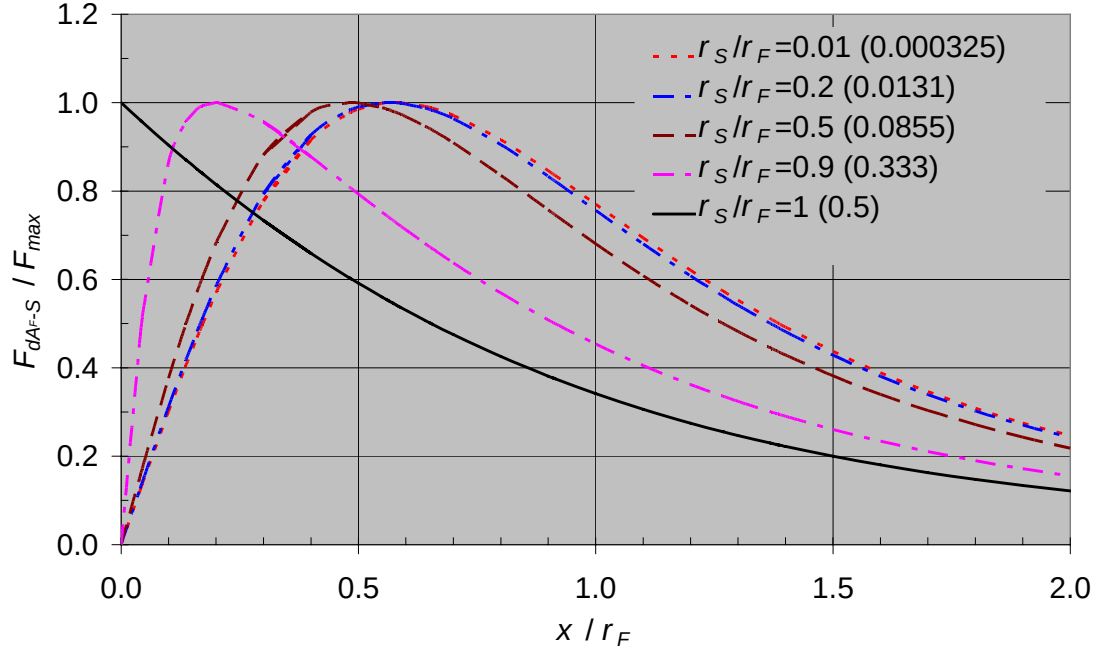


Figure 3.2 Calculation of normalised configuration factor along the furnace tube with $r_S/r_F = 0.01, 0.2, 0.5, 0.9$ and 1 respectively. In the brackets are the peak values before normalisation.

Then the radiation received by a detector from the sample surface can be calculated by

$$S_{Sm}(\lambda) = A \left[\varepsilon_S L(\lambda, T_S) + R_S S_{refl} \right] \quad (3.3)$$

where

- A: instrumental factor dependent on the optical detection system;
- R_S : reflection coefficient of radiation at the sample surface that can be angle and wavelength dependent, $R_S = 1 - \varepsilon_S$ is assumed and hold when the sample surface is diffuse;

Calculations have been made to evaluate the effect of background radiation on target temperature measurement with various parameters. $\varepsilon_{Ftrue} = 1.0$ is assumed, so that there is no radiation exchange between different parts of the furnace surface. The calculation was performed using the following procedure:

- Choose parameters for a measurement system
- Calculate radiation emitted by sample surface
- Calculate radiation distribution along the furnace wall
- Where required, add 5% random noise (normal distribution with $\sigma = 1$) to the calculated signals
- Calculate the signal contributed by radiation emitted by sample surface and reflected radiation from furnace wall (with or without added random noise)

- Using calculated signals of furnace wall and combined signal from sample surface to calculate sample temperature and emissivity
- Change the wall position for reference signal and repeat sample temperature (T_{Sm}) and emissivity (ε_{Sm}) calculation as above.
- Compare calculated sample temperature (T_{Sm}) and emissivity (ε_{Sm}) with those true values (T_{Strue} and ε_{Strue}) and find differences between them.

Parameters used in the calculation are:

- Furnace length: $2H = 1000$ mm
- Furnace diameter: $2r_F = 100$ mm
- Sample diameter: $2r_S = 10$ mm
- Sample true temperature: $T_{Strue} = 900$ K
- Sample true emissivity: $\varepsilon_{Strue} = 0.7$
- Sample position: middle of furnace
- Furnace true emissivity: $\varepsilon_{Ftrue} = 1.0$
- Wavelength range: 900 - 1700 nm in 10 nm steps

Table 3.1 presents the calculated errors in the RTHAT sample temperature and emissivity measurements, due to the reflected background radiation from the furnace wall at temperatures $T_F = 800, 1200$ and 1600 K respectively. In a second calculation, a 5% random noise was added to both target and background radiation to evaluate the effect of noise on the temperature measurement. The calculation shows that, when there was no random noise, errors in measurements of sample temperature ΔT_{Sm} and emissivity $\Delta \varepsilon_{Sm}$ are small. Those small errors may be caused by the number (81) of signals used in the calculation and represent the calculation limits of the programme. When a 5% random noise is added to the simulation signals, the errors in target temperature increased significantly when $T_F = 1200$ and 1600 K.

Table 3.1 Errors in sample temperature and emissivity calculations ($T_{Strue} = 900$ K and $\varepsilon_{Strue} = 0.7$)

Furnace temperature T_F / K	Without noise		With 5% noise	
	$\Delta T_{Sm} / \text{K}$	$\Delta \varepsilon_{Sm}$	$\Delta T_{Sm} / \text{K}$	$\Delta \varepsilon_{Sm}$
800	1.0	0.005	0.5	0.016
1200	-2.0	0.011	8.5	0.017
1600	-1.7	0.012	8.3	0.012

Further investigation was carried out with non-uniform temperature profiles along the furnace tube. The temperature profile used can be described by the following equation (see Figure 3.1):

$$T_F(x) = \frac{T_{F0}}{1 + \left(\frac{x}{H}\right)^2} \quad (3.4)$$

where T_{F0} is the maximum furnace temperature at the position next to the sample.

The furnace temperature decreases from the maximum T_{F0} to the half $T_{F0}/2$ at the open end of furnace tube. Figures 3.3-4 show the errors in the sample temperature and emissivity calculated from simulated signals, caused by the reflected radiation from the non-isothermal furnace wall. Calculations were performed with and without 5% random noise added on the calculated signals and, as a result, additional errors (similar to those in Table 3.1) were observed consistently due to the noise in the temperature and emissivity calculations.

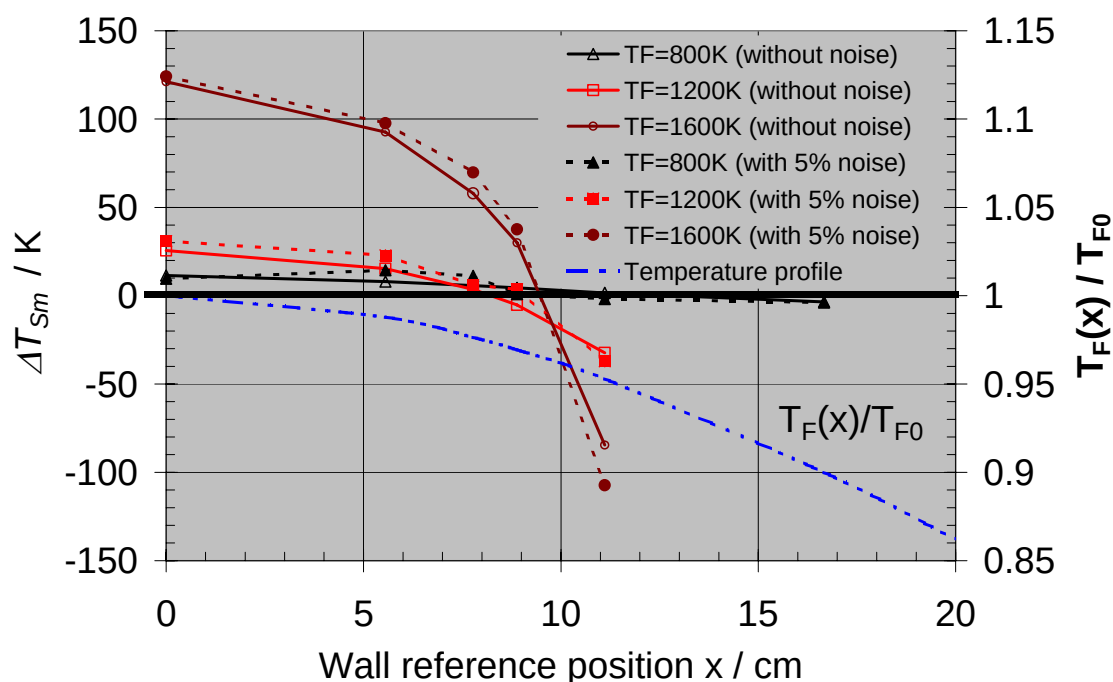


Figure 3.3 Calculated target temperature errors versus position of reference point on furnace wall at where the background pyrometer looks. Parameters used for the calculation are $T_{Strue} = 900$ K and $\varepsilon_{Strue} = 0.7$, $T_F = 800$, 1200 and 1600 K respectively.

The calculation indicates that, overall, the temperature errors caused by the radiation from the furnace wall are dramatically larger than those presented in Table 3.1 for uniform furnace temperature profiles. Both figures show that the errors increase with the furnace temperature and vary sensitively with the position on the furnace wall where the reference background signal is taken. In general, the temperature errors change from positive to negative when the reference point on the furnace wall moves away from the sample. This indicates that, to achieve the error in temperature measurement within a required range, a region on the furnace wall can be found from where the detected radiation can effectively represents the reflected background radiation at the target surface. Optimal positions of the reference signal on the furnace wall can be determined from the calculation where the temperature errors are close to zero, which vary slightly with the furnace temperature. At high furnace temperatures

of 1200 and 1600 °C, it was found that the calculation errors increase fast when the distance of the reference position is larger than 11 cm where the furnace temperature drops to about 95% of its maximum temperature. This shows that, beyond this distance, the radiation from furnace wall cannot effectively represent the reflected radiation at the sample surface.

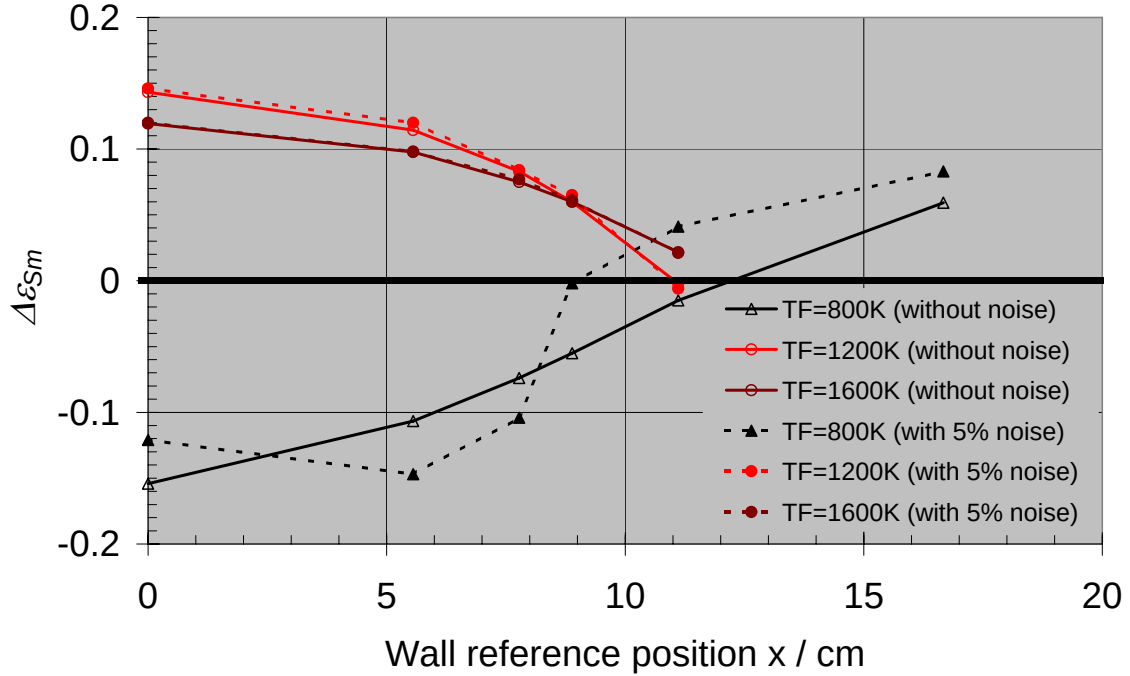


Figure 3.4 Calculated target emissivity errors versus position of reference point on furnace wall. Parameters used for the calculation are $T_{Strue} = 900$ K and $\epsilon_{Strue} = 0.7$, $T_F = 800, 1200$ and 1600 K respectively.

3.2 Sensitivity analysis of multi-wavelength pyrometry

The spectral RTHAT technique can be seen as a natural extension development of conventional multi-wavelength pyrometry as both determine target temperature from radiance measurements at a number of wavelengths. Therefore it is beneficial to the RTHAT development if the advantages of multi-wavelength pyrometry can be inherited and its shortcomings overcome or avoided.

The single wavelength pyrometry is popular for temperature measurement of targets in difficult environments where contact methods of temperature measurement cannot be used. However, requirement of prior knowledge of target emissivity severely restricts its use in many industrial applications. The multi-wavelength pyrometry is proposed to overcome this difficulty and so the temperature can be measured without the need to know the target emissivity. In the multi-wavelength pyrometry, m thermal radiation signals are measured independently at m different wavelengths. The signals are dependent on target emissivity at those wavelengths and its temperature. Without prior knowledge of target emissivity, it is impossible from m measurements to determine $m+1$ unknown parameters (*i.e.* m emissivity values and the temperature of

target). Therefore the problem is ill conditioned and underdetermined. To deal with this under-determination, an approximation is often made of a $(m-2)$ th order polynomial function for the target emissivity dependence on wavelength. Experience shows that sometimes this approximation can cause large uncertainties in temperature measurement using multi-wavelength pyrometry. To demonstrate this a few examples are investigated here.

In this sensitivity analysis of multi-wavelength pyrometry, the procedure is outlined below:

- Find emissivity versus wavelength values for a material to be studied.
- Let the target be at a *true* temperature (T_{true}). Choose a set of m wavelengths (λ_n) with corresponding emissivity (ϵ_n^{true}) values.
- Calculate the thermal radiation signals using Planck's law with T_{true} and ϵ_n^{true} values.
- Calculate the measured temperature ($T_{measured}$) by minimising χ^2 functional equation.
- Calculate the error due the approximation $\Delta T = T_{true} - T_{measured}$.

A copper at $T_{true} = 1000$ K and a tungsten at $T_{true} = 1600$ K are studied and the results are summarised in Tables 3.2 and 3.3. In those tables, target emissivity values at chosen wavelengths are given and indicated for use in each pyrometer calculation.

During the investigation, there were difficulties in the calculation using a Matlab programme, in which the commands “fminsearch” and “polyfit” did not converge well when the number of wavelengths was three or greater. The calculated results were also sensitive to the starting values used in the programme.

In Tables 3.2 and 3.3, the values of R^2 (a goodness assessment of data fitting) were also computed for the fitting of emissivity data used in the calculation. As expected, direct correlation can be found between ΔT and R^2 , i.e. the larger R^2 the smaller ΔT . For the copper, the temperature error decreased from about 83 °C with two-wavelength pyrometry to 41 °C with three-wavelength pyrometry. It further decreased to -0.79 °C and -0.07 °C when the number of wavelengths increased to five and eleven respectively. Those remarkably good results are not representative because, in a similar case of tungsten, the temperature error did not improve further when the number of wavelengths increased to five or eight meanwhile the fitting of emissivity data was excellent.

In the study of tungsten, the analysis is also performed with the emissivity polynomial kept to order 2 for five- and eight-wavelength pyrometry measurements. Noticeably improved temperature errors -10.9 °C and -14.7 °C were achieved while their R^2 values of emissivity data fitting were similar.

The contours of χ^2 versus two parameters of T , c_1 and c_2 are plotted in Figure 3.5 for the case of copper at $T_{true} = 1000$ K and with three wavelengths (see Table 3.2), to examine if there are valleys in these plots. A valley indicates strong correlations between the fitted parameters in an ill-conditioned problem, and then small errors in the measured signals can cause big errors in the fitted parameters (i.e. T , c_i 's).

Table 3.2 Summary of sensitivity analysis of multi-wavelength pyrometry on a copper material at $T_{true} = 1000$ K (emissivity data for copper are found from copper data table 49, curve 13 in the data book edited by Touloukian and DeWitt, 1970).

$\lambda / \mu\text{m}$	ε	Two wavelengths $m=2$	Three wavelengths $m=3$	Five wavelengths $m=5$	Eleven wavelengths $m=11$
1.0	0.48	•	•	•	•
1.1	0.51				•
1.2	0.54			•	•
1.3	0.56				•
1.4	0.6				•
1.5	0.62		•	•	•
1.6	0.65				•
1.7	0.67			•	•
1.8	0.70				•
1.9	0.70				•
2.0	0.70	•	•	•	•
$\Delta T / ^\circ\text{C}$ (ε fitting: order $m=2$)		82.88	41.13	-0.79	-0.07
R^2 (ε fitting: order $m=2$)			0.8796	0.9453	0.9999

In summary, the outcome of this study is in-line with the conclusions of previous studies [*e.g.* Coates, 1981], *i.e.* increasing the number of wavelengths does not reduce the ΔT value in conventional multi-wavelength pyrometry.

The results show that there are two potential problems with conventional multi-wavelength pyrometry:

- The approximation made of the dependence of emissivity on wavelength can lead to unacceptably large uncertainties in the measured temperature in both investigated cases.
- The multi-wavelength pyrometry is ill conditioned. The χ^2 contour plots exhibit the valleys and shallow minima, and thus, small errors in the measured signals can lead to large errors in measured temperature value.

Table 3.3 Summary of sensitivity analysis of multi-wavelength pyrometry on a tungsten material at $T_{true} = 1600$ K (emissivity data for tungsten are found from tungsten data table 234, curve 18 in the data book edited by Touloukian and DeWitt, 1970).

$\lambda / \mu\text{m}$	ε	Two wavelengths $m=2$	Three wavelengths $m=3$	Five wavelengths $m=5$	Eight wavelengths $m=8$
1	0.39	•	•	•	•
1.2	0.344				•
1.27	0.328			•	•
1.35	0.310				•
1.5	0.28		•	•	•
1.6	0.263				•
1.8	0.234			•	•
2	0.21	•	•	•	•
$\Delta T / ^\circ\text{C}$ (ε fitting: order $m-2$)		260	89.23	-123.67	-57.92
$\Delta T / ^\circ\text{C}$ (ε fitting: order 2)				-10.87	-14.74
R^2 (ε fitting: order $m-2$)			0.9958	1.0000	1.0000
R^2 (ε fitting: order 2)				0.9999	0.9999

In order to avoid uncontrolled divergence in the high-order polynomial function of target emissivity, in this work, a linear dependence of target emissivity on wavelength is used to fit measured signals over a small band (*e.g.* 0.1 μm bandwidth) of wavelength. (This assumption of emissivity usually is good approximation for many condensed materials at high temperatures.) Then both target temperature and emissivity can be calculated. When the calculation is performed over all measured signals, two sets of values for target temperature and emissivity are obtained from signals in different wavelength bands. In order to assess the goodness of data fitting, a χ^2 of fitting residuals can be calculated. By comparing calculated χ^2 values, best-fit region of radiation signal can be identified and thus the target temperature of improved reliability is found by averaging the calculated emissivity values weighted by their χ^2 values.

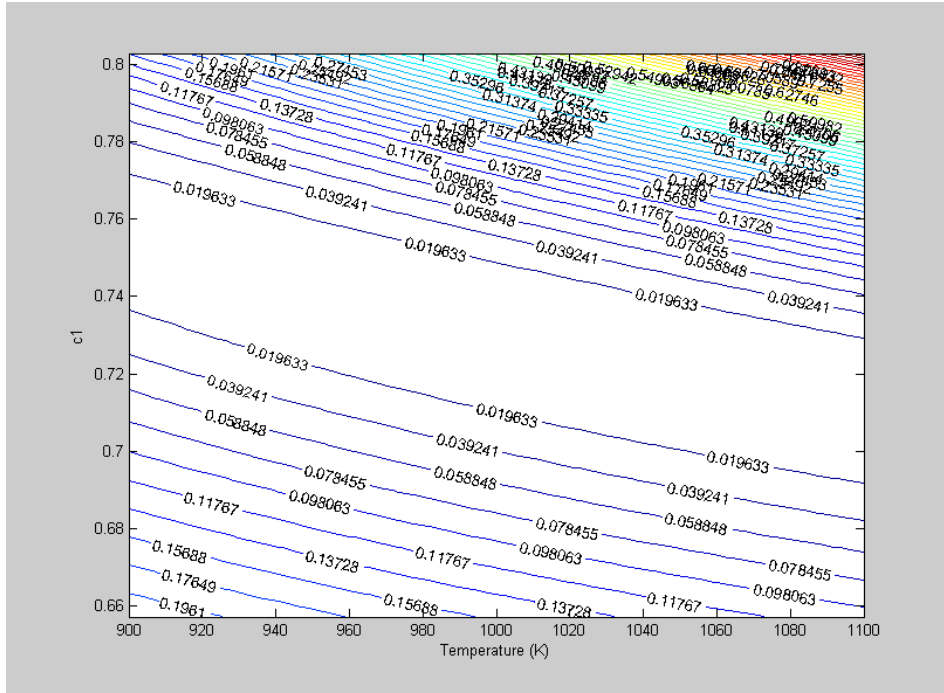


Figure 3.5 (a) Contour plots of χ^2 versus T and c_1 the case of copper with $T_{true} = 1000$ K and three wavelengths. (see Table 3.2)

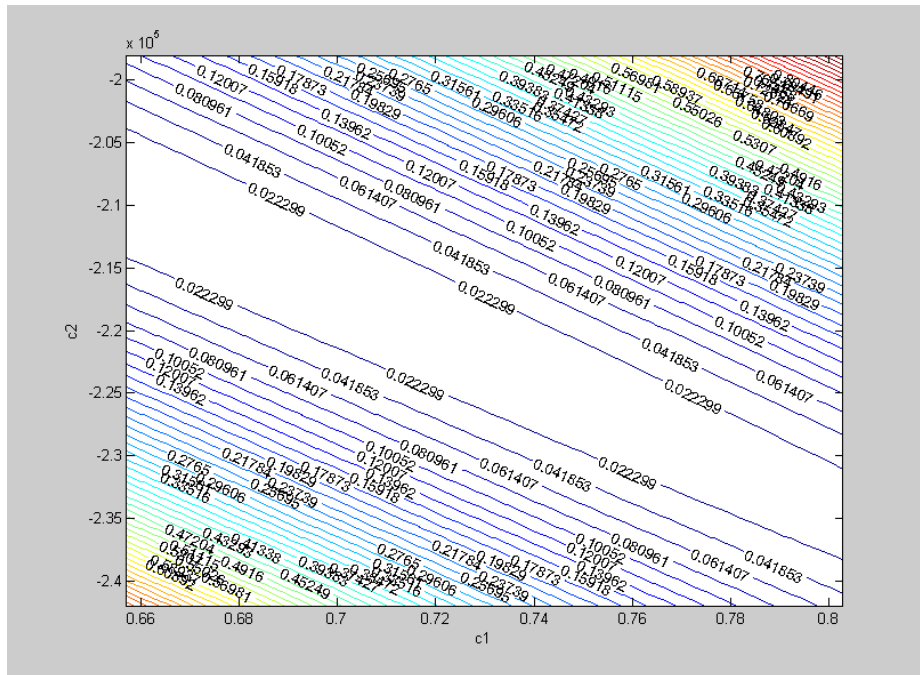


Figure 3.5 (b) Contour plots of χ^2 versus c_1 and c_2 for the case of copper with $T_{true} = 1000$ K and three wavelengths. (see Table 3.2)

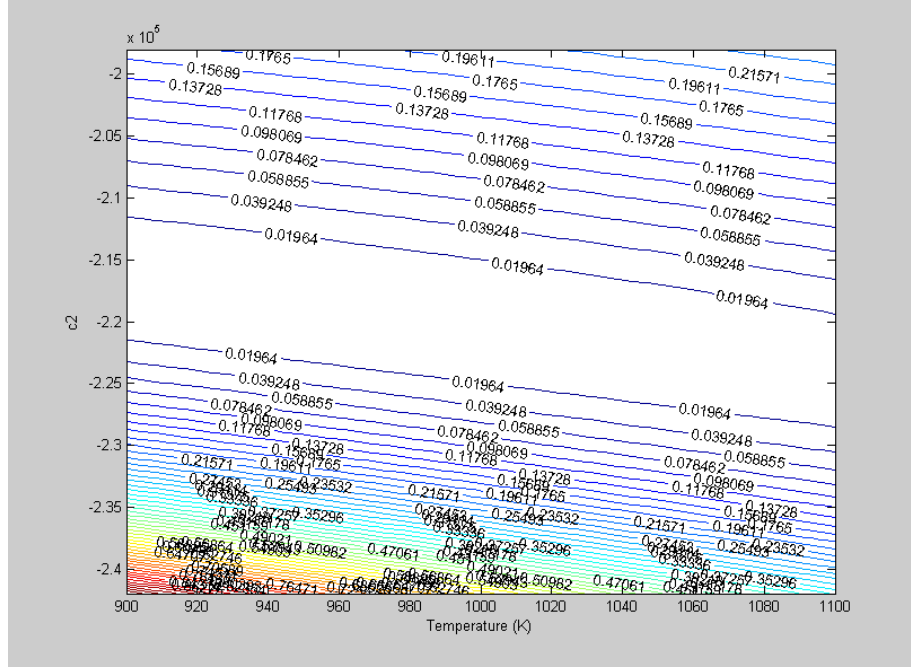


Figure 3.5 (c) Contour plots of χ^2 versus T and c_2 for the case of copper with $T_{true} = 1000$ K and three wavelengths. (see Table 3.2)

3.3 Sensitivity analysis of spectral RTHAT

As discussed in Section 2, in spectral RTHAT, the measured radiation signal from the target surface consists of two components, one emitted by the target surface and the other reflected from the background radiation. The background radiation is also measured directly for use as a reference signal in the target temperature determination.

In this sensitivity analysis of spectral RTHAT pyrometry, the following procedure is used:

- Find emissivity versus wavelength values for a material to be studied.
- Let the target be at a *true* temperature (T_{true}). Choose a set of m wavelengths (λ_n) with corresponding emissivity (ε_n^{true}) values.
- Calculate the signals from thermal radiation emitted by target surface with T_{true} and ε_n^{true} values.
- Calculate the reference signals from background radiation.
- Calculate the signals from reflected background radiation.
- Combine two components of signal measured from the target surface.
- Calculate the measured temperature ($T_{measured}$) by minimising χ^2 functional equation.
- Calculate the error in the temperature measurement $\Delta T = T_{true} - T_{measured}$.

A measurement system similar to that shown in Figure 3.1 is used in the analysis. The target is a disc of 50 mm in diameter and is assumed to be a greybody with emissivity 0.5 at all studied wavelengths at a 1000 °C temperature. The inner diameter of tube furnace is 50 mm and the distance between the target surface to the open end of furnace is $H=100$ mm. The emissivity of the furnace wall is 1. A simple triple-spectral-area pyrometer (TRISAP) is used in the investigation with three working wavelengths of 1.0, 1.5, and 2.0 μm . Similar tendencies in the results have been obtained for a ten-wavelength pyrometry system.

In this analysis, the target temperature is 1000 °C and the maximum background temperature is 1600 °C. Between these two temperatures, the differences in their Planckian radiation are about 37.3, 11.2 and 6.1 times at 1.0, 1.5 and 2.0 μm wavelengths respectively. Therefore the background radiation from the furnace is much larger than that emitted by the target surface in both investigated cases below, and there would be unacceptably large errors in target temperature measurement if conventional multi-wavelength pyrometry were used.

Using the RTHAT method, the contour plot of χ^2 versus T_{measured} and r_0 is shown in Figure 3.6 for a target at 1000 °C and its isothermal background temperature at 1600 °C using a MATLAB programme, where r_0 is a coupling factor of reflected background radiation to the detection system. A valley can be seen in the plot with a shallow minimum at $T=1000$ °C and $r_0 = 6$ at the centre of the plot. The valley and shallowness of the minimum imply that small errors in the measured signal can lead to large errors in T_{measured} in this case of strong background radiation.

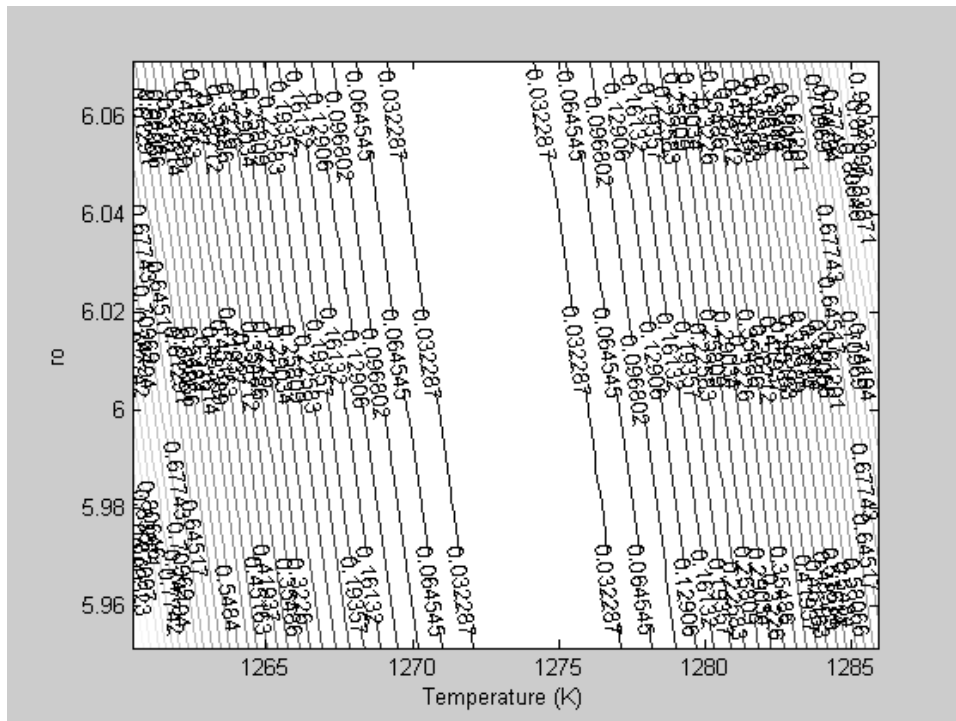


Figure 3.7 shows the plot of fitted target temperature $T_{measured}$ as a function of isothermal background temperature, and demonstrates that a 1 °C error in the background temperature gives a 25 °C change in the $T_{measured}$ value in this case of strong background radiation.

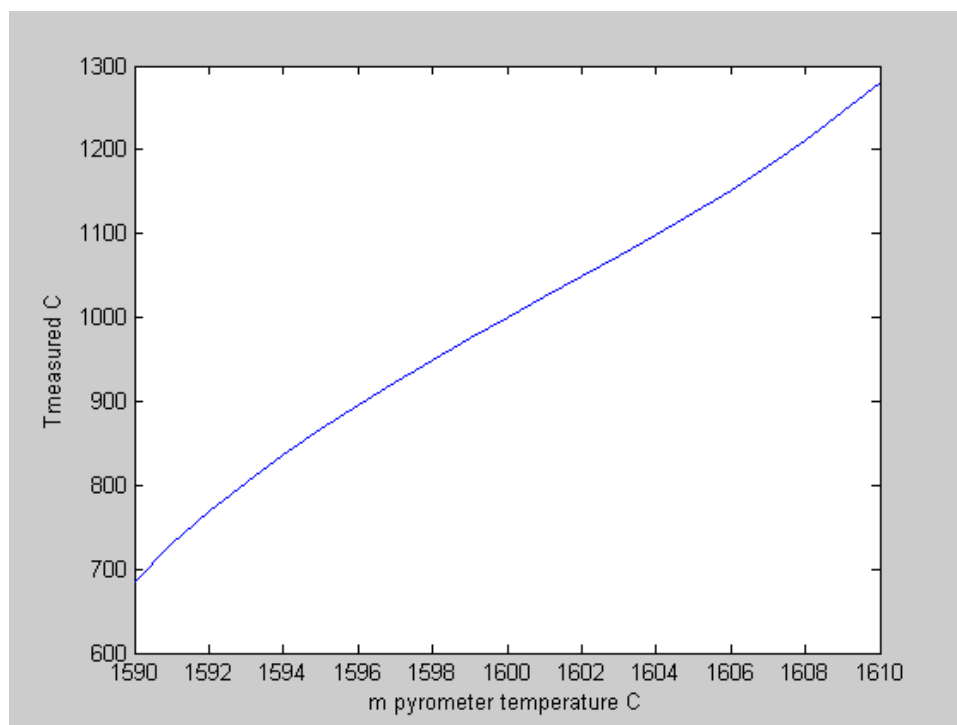


Figure 3.7 Plot of fitted target temperature $T_{measured}$ as a function of isothermal background temperature.

To show how sensitive the target temperature measurement is to the reference position on furnace wall from where the reference signal is taken, a non-uniform temperature profile on the furnace wall is used in that the furnace temperature decreases according to a quadratic equation from 1600 °C at the position next to the target to 1500 °C at the open end of furnace. Figure 3.8 shows the plot of fitted target temperature $T_{measured}$ as a function of x (i.e. the position on furnace wall) where the reference signal is taken, and demonstrates that the fitted “RTHAT temperature” $T_{measured}$ can be sensitive to the position of the reference signal detection on the furnace wall in this case of strong background radiation.

In summary, the study shows that large temperature errors can exist using the RTHAT technique in two extremely difficult cases where the background radiation is much larger than that emitted by the target surface. The technique may be improved by exploiting other additional structures in the background radiation (e.g. spectral lines emitted by combustion gases), there will be a deeper minimum in the χ^2 contour surface and therefore smaller errors in the temperature measurement.

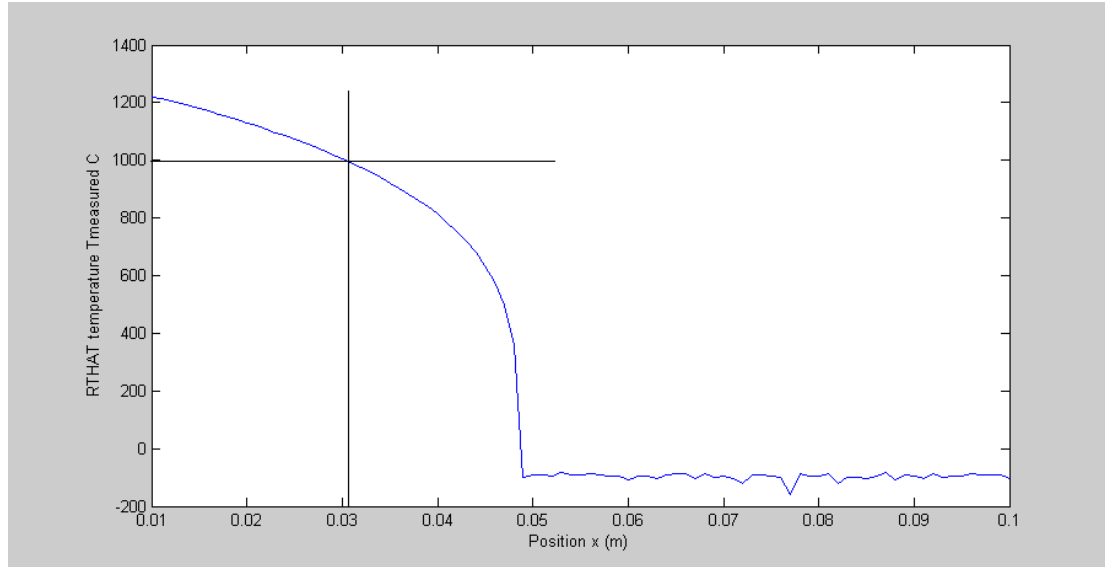


Figure 3.8 Plot of fitted target temperature $T_{measured}$ as a function of x with a non-uniform temperature profile of furnace wall varying from 1600 °C to 1500 °C.

4 Portable spectral RTHAT apparatus

A portable RTHAT pyrometer has been built for correcting for reflected radiation error in temperature measurement by using the spectral information in the background radiation. It has the advantages: (i) passive technique; (ii) low cost; (iii) without the need for a priori knowledge of the target emissivity and; (iv) no signal saturation difficulty for high temperature measurement.

As shown in Figure 4.1, the RTHAT apparatus consists of a laptop PC, an optical detection head described in Section 1.1 earlier and an InGaAs array spectrometer (Model NIR-256L-1.7-USB, Control Development Inc.). The spectrometer has 256 InGaAs detector pixels to sensitively measure radiation over a wavelength range of 0.9 - 1.7 μm and a spectral resolution of about 0.003 μm per pixel. The integration time of detector can be adjusted from 10 μs to 16 s according to the intensity of radiation signal, which effectively overcome the signal saturation difficulty for high temperature measurement. The radiation is collected using the detection head and delivered via a optical fibre to the spectrometer for measurement. The apparatus can be easily customised for a particular application. Preliminary tests show that the apparatus can detect radiation signal from a target at temperatures as low as 300 °C.

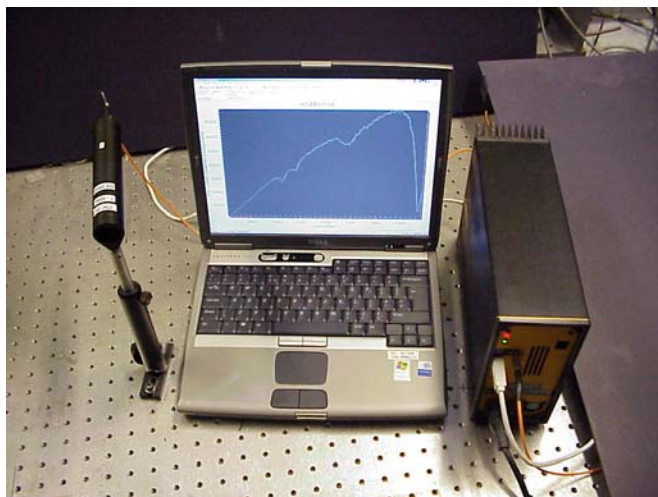


Figure 4.1 RTHAT apparatus consisting of a laptop PC, an InGaAs array spectrometer and a optical detection head.

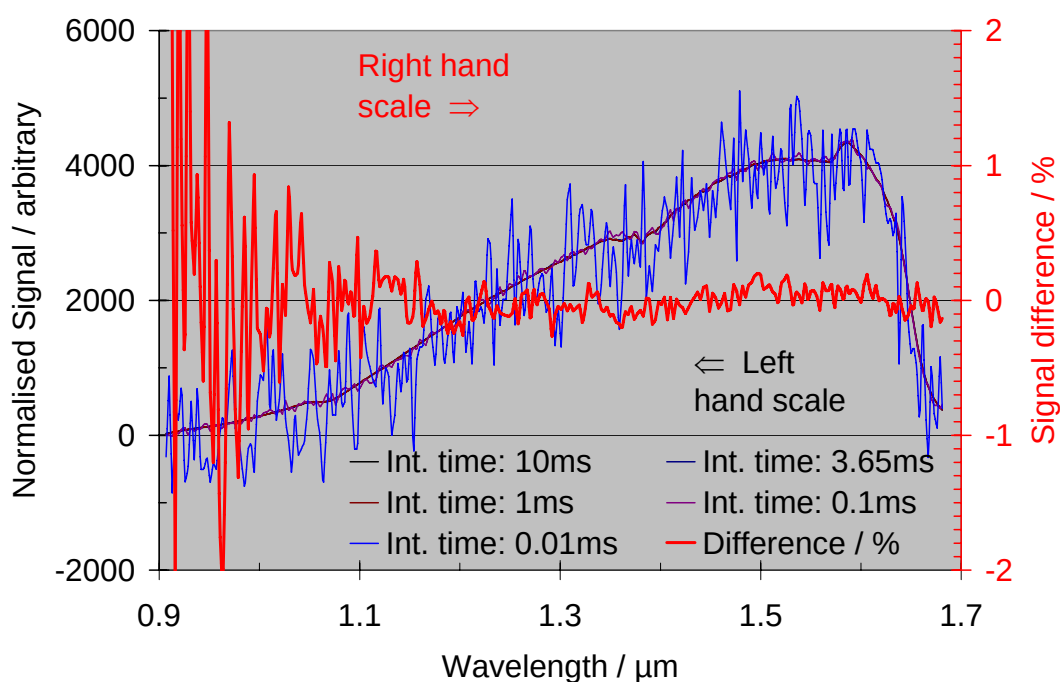


Figure 4.2 Radiation signals measured from an NPL standard blackbody cavity at 1000 °C, normalised by the integration time of spectrometer varying from 0.01 to 10 ms. The red line is the relative difference between those signals with 3.65 and 10 ms integration times.

The apparatus has been calibrated using an NPL standard blackbody cavity at temperatures from 500 to 1000 °C with 100 °C intervals to check its performance and to determine the spectral response function. Figure 4.2 shows radiation signals measured from the blackbody at 1000 °C, normalised by the integration time of spectrometer. The figure shows the excellent signal stability and linearity of the

apparatus over a large range of signals with the integration time changing from 0.01 to 10 ms. Most of discrepancies between any two curves are within 2%. Measurements indicate the measurement uncertainty increases towards shorter wavelengths because of weak radiation signals at the temperatures.

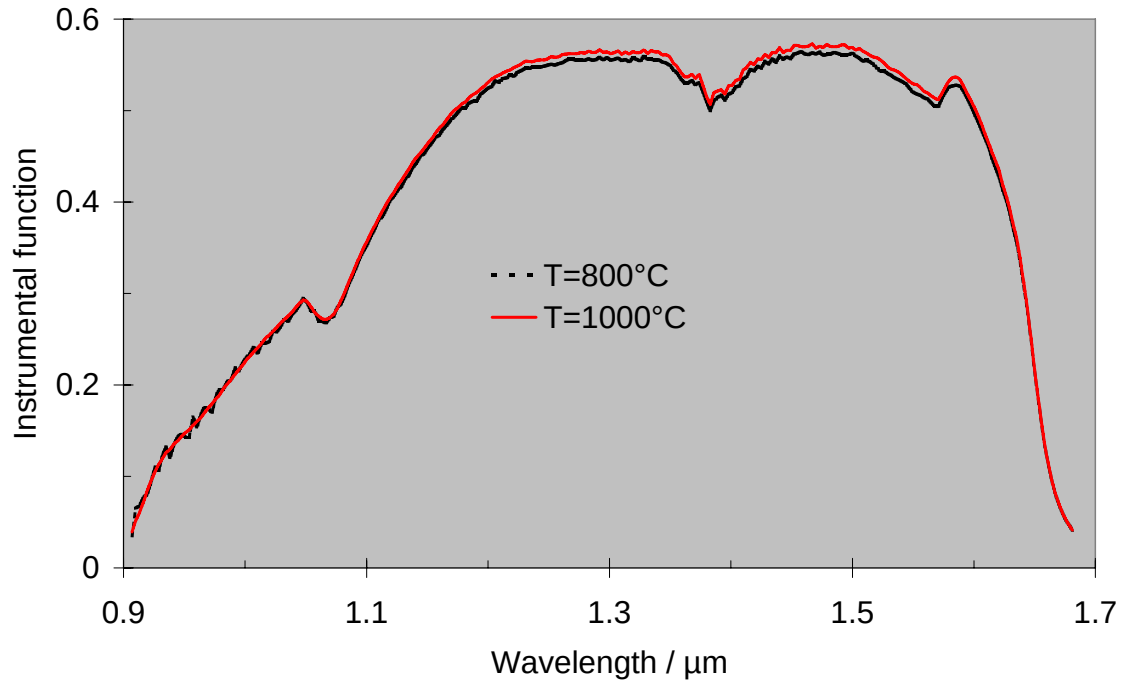


Figure 4.3 Instrumental factor B in Equation (2.1) of the RTHAT apparatus determined by comparison between Planck's law and spectral signals measured from an NPL standard blackbody cavity at 800 and 1000 °C respectively, both with a 10 ms integration time of spectrometer.

Measurement procedure: during a RTHAT measurement, radiation signals from a sample surface (S_0) and its background (S_b) are measured separately. The instrumental function in Figure 4.3 is applied to the measured signals to correct for the spectral response of instrument. With a diffuse sample surface and the known temperature profile for the furnace tube, a theoretical model can be developed to consider the reflected background radiation in the measured sample signal. Using the least-square curve-fitting technique, sample temperature (T) and emissivity (ϵ_λ) can be computed by minimising the chi-square value calculated from the measured signals and theoretical model. The measurement procedure is outlined by the following measurement sequence:

- a) Set up measurement system to attain stable conditions for the target and its background.
- b) Set up the spectral RTAHT apparatus, including the computer and spectrometer (also refer to operation manuals).
- c) Aim the detection head to the area on the target surface to be measured.
- d) Take a signal from the target for trial and adjust measurement parameters (e.g. integration time of spectrometer) in the apparatus for optimal signal quality.

- e) Make measurement on the target and record measurement conditions/ parameters and store the measured signals to an electronic file.
- f) Aim the detection head to the chosen area on the background surface from where the best representative background radiation is to be measured.
- g) Choose a reference position on the background surface. Repeat d) and e) above for the reference signal measurement of background radiation.
- h) Apply the response function of the apparatus to measured signals.
- i) Use Matlab computer programme to calculate target temperature and emissivity, by minimising the chi-square of data fitting residuals between the measured signals and theoretical model.
- j) Check the quality of the best-fit sample temperature and emissivity by examining the distribution of chi-square values over ranges of sample temperature and emissivity.

5 Experiments

To validate the apparatus, three experimental tests have been carried out on several targets under different conditions, including (i) a platinum/ Inconel assembly target in a small furnace; (ii) a FeCrAlloy sample in an NPL high temperature facility; and (iii) a specially designed Inconel target in a heat pipe furnace system.

5.1 Test with platinum/ Inconel assembly target

A platinum/ Inconel assembly target shown in Figure 5.1 consists of two $\phi 24 \times 48$ semi-cylinders of oxidised Inconel. In the upper part, a hole is made from the front face to fit a $\phi 8 \times 20$ mm platinum rod. On the front face of the lower part, a $\phi 3 \times 9$ hole is drilled for use as a blackbody cavity. The sample assembly is placed on an alumina tubing of $\phi 26$ ID, $\phi 32$ OD and 150 mm long in the centre of a heating furnace (Carbolite type: MTF 10/25) (also see Figure 1.1 for this set-up arrangement).

The measurement was carried out under the following conditions:

- Furnace temperature was set to 773.15 K.
- Temperature measured by a type-K thermocouple immediately behind the front Inconel surface: 700.33 ± 0.15 K.
- Temperature measured by a type-K thermocouple immediately behind the platinum rod: 742.17 ± 0.18 K.
- Focused bulb light impinges the sample surface at an incident angle of 30° from the normal to the sample surface (see Figure 5.2).
- Radiation signal was detected at an angle of 10° from the normal to the sample surface.
- The bulb was powered by using a DC power supply with an output voltage varying from 0 to 3.65 volts.
- The measurements were carried out in the order of platinum surface, Inconel surface, blackbody cavity and bulb filament.

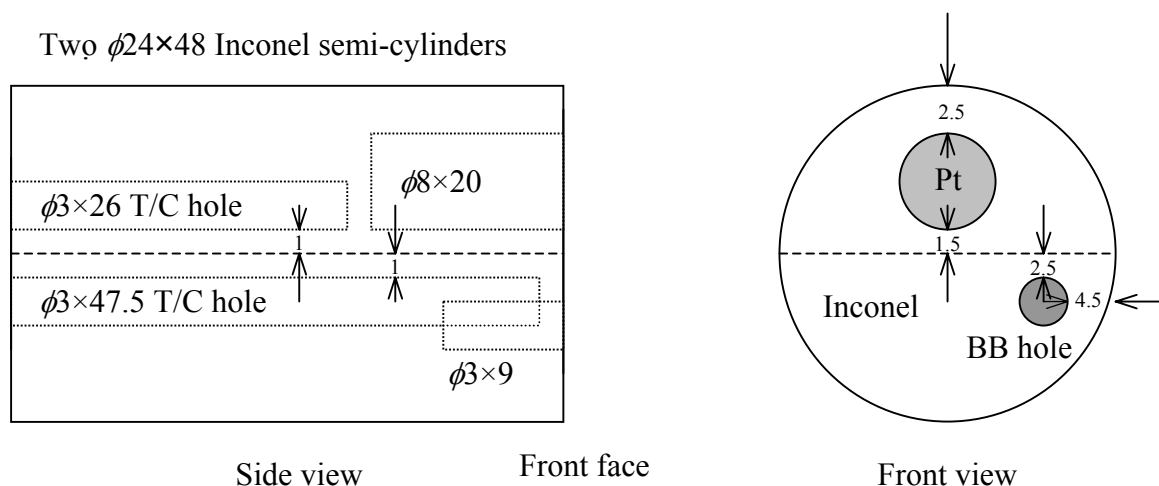


Figure 5.1 Design of platinum/Inconel assembly target consisting of two $\phi 24 \times 48$ Inconel semi-cylinders and a $\phi 8 \times 20$ platinum rod (dimensions are in mm and drawing is not to scale).

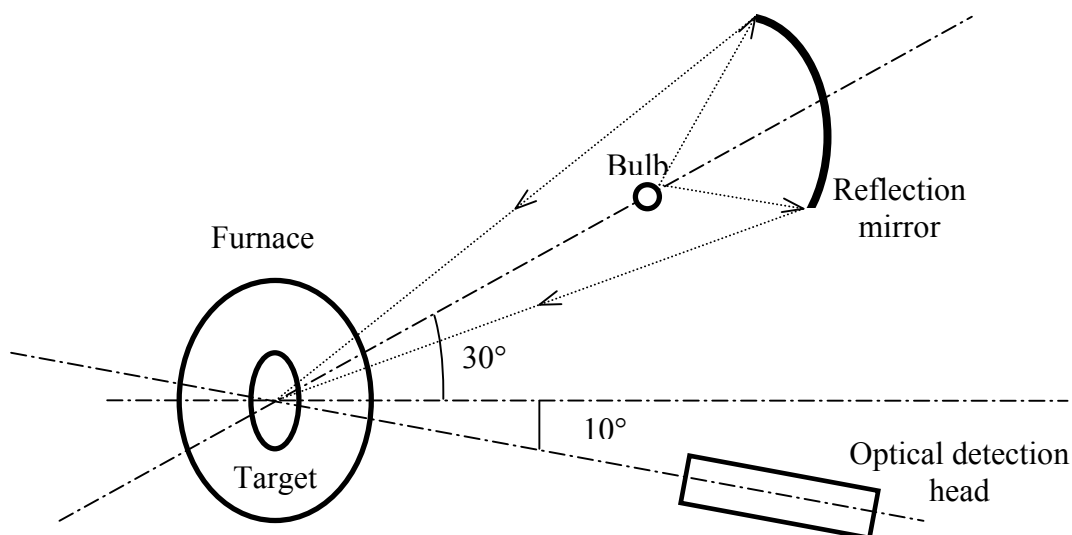


Figure 5.2 Experimental arrangement of RTHAT measurements using a bulb radiation source (also see Figure 1.1).

5.1.1 Measured radiation signals

Figure 5.3 shows radiation signals versus bulb voltage, measured from bulb filament, blackbody cavity, Inconel and platinum surfaces respectively. The signals (S) are normalised by the spectrometer integration time, and plotted in $\ln(\lambda^5 S)$ as functions of wavenumber (λ^{-1}) after multiplied by λ^5 (according to Wien's approximation, the plot has a linear dependence on wavenumber at short wavelengths for radiation from an

ideal blackbody or a greybody material.). Although some noise can be observed, no gas absorption lines are noticed.

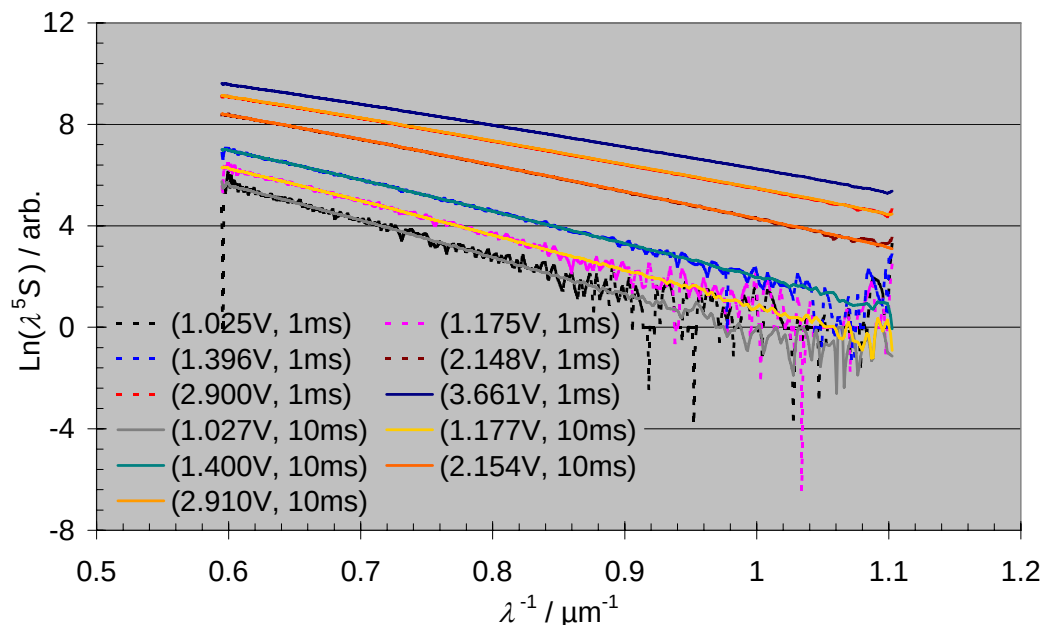


Figure 5.3(a) Normalised radiation signal $\ln(\lambda^5 S)$ versus λ^{-1} , after detection response correction, measured from the bulb filament. In the brackets of legends, the first column is the voltage of bulb and the second column is the spectrometer integration time.

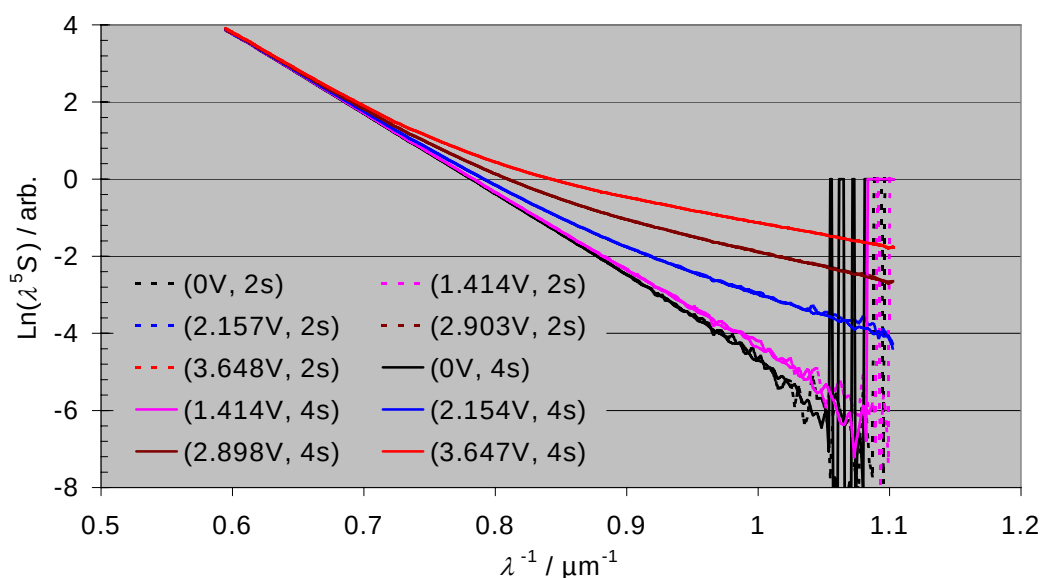


Figure 5.3(b) Normalised radiation signal $\ln(\lambda^5 S)$ versus λ^{-1} , after detection response correction, measured from blackbody cavity impinged by bulb radiation.

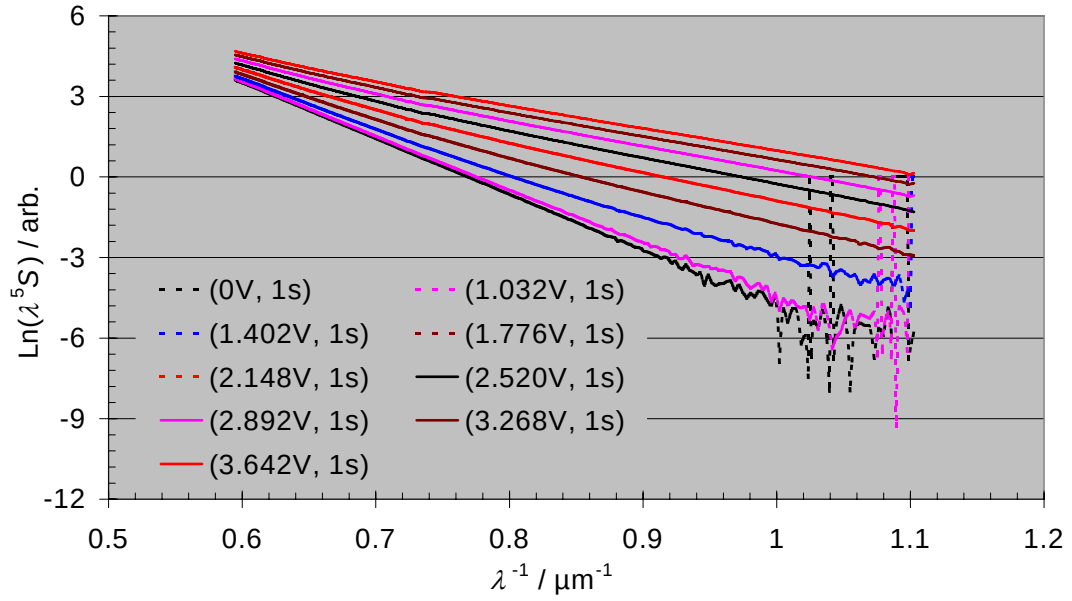


Figure 5.3(c) Normalised radiation signal $\ln(\lambda^5 S)$ versus λ^{-1} , after detection response correction, measured from the Inconel surface impinged by bulb radiation.

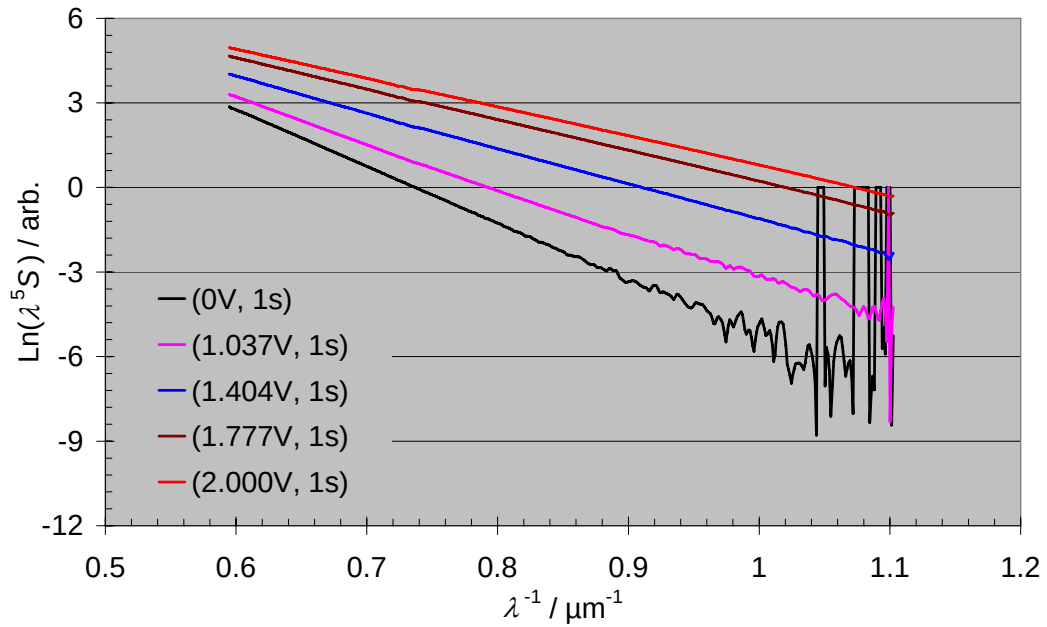


Figure 5.3(d) Normalised radiation signal $\ln(\lambda^5 S)$ versus λ^{-1} , after detection response correction, measured from platinum surface impinged by bulb radiation.

Bulb signal: radiation signals measured directly from the bulb filament, powered by 1.025 to 3.661 volts, are presented in Figure 5.3(a) after normalised by spectrometer integration times of 1 to 10 ms. Significant improvement in signal-to-noise ratio can be seen when the integration time increased, while no obvious changes are observed in the spectra of radiation. This measurement confirms the excellent linearity and stability of the RTHAT detection system over a large signal range.

Blackbody signal: radiation signals presented in Figure 5.3(b) show that the signal measured from the blackbody cavity can be significantly affected by the impinging bulb radiation. This is probably due to a small part of scattering bulb radiation at the inner blackbody walls that reached the RTHAT probe head and was detected by the spectrometer. Since the radiation spectrum shifts to short wavelengths when temperature increases, the blackbody signal was affected relatively more at short wavelengths (or high wavenumbers) when the bulb voltage increased.

Inconel signal: as the oxidise Inconel surface reflects and scatters the bulb radiation, the radiation signal detected from the Inconel surface was affected over all wavelengths as shown in Figure 5.3(c). The measurement shows that, for instance when the bulb was powered by 2.892 volts, the components of reflected bulb radiation were larger than those emitted by the Inconel surface.

Platinum signal: due to its high reflectivity, the platinum surface reflects and scatters bulb radiation strongly. The components of the reflected bulb radiation became dominant in the signal detected from the platinum surface when the bulb voltage was higher than 1.404 volts as shown in Figure 5.3(d).

5.1.2 Signal analysis

Using the method outlined in Section 3, the temperature and emissivity of targets are estimated from the measured radiation signals, and the results are shown in Figures 5.4 - 5.7.

As seen in Figure 5.3, if random noise is considered in weak signals, all measured radiation signals ($\ln(\lambda^5 S)$) are approximately linearly dependent on wavenumber (λ^{-1}) when there is no background radiation contamination. Therefore it is a reasonable approximation to use an assumed constant or linear dependence of target emissivity on wavelength in curve-fitting measured signals over a small band (e.g. 0.1 μm bandwidth) of wavelength. Both target temperature and emissivity can then be calculated. Furthermore the wavelength range of all signals can be divided into many small bands in each of that a pair of target temperature and emissivity can be computed, resulting in a set of calculated target temperatures. Also, in order to assess the goodness of data fitting, a chi-squared value of fitting residuals can be calculated and used as weighting factor in the determination of the final target temperature with an improved measurement uncertainty.

Comparing with the conventional multi-wavelength pyrometry techniques, the above data analysis method of spectral RTHAT method can determine both the target temperature and emissivity with better reliability improved by assessment of the chi-squared value of fitting residuals. Since a constant or linear dependence of target

emissivity on wavelength is used in the data analysis, wildly uncontrolled divergence in the temperature calculation occurred in conventional multi-wavelength pyrometers is also less likely to happen in the RTHAT method.

For the radiation signal measured from the bulb, no background radiation was considered, as the radiance temperature of bulb filament was much higher than the ambient temperature. According to their power voltages, bulb radiation signals also are used as the reference signal of background radiation in the data analysis of radiation signals measured from blackbody cavity, Inconel and platinum.

Using the RTHAT data analysis method outlined earlier in this section, Figure 5.4 shows the temperature and emissivity measurements of bulb filament, calculated from radiation signals presented in Figure 5.3(a). The results show that the temperature measurements are stable when the integration time of spectrometer was changed. It also demonstrates that long integration times improve signal quality, evidenced by smaller departures from the fitted curve.

The emissivity of the filament is calculated at 1 and 1.6 μm wavelengths as shown in Figure 5.4(b). Similar improvements can be seen in the emissivity measurements when the integration time of spectrometer was increased. Compared with the temperature results, the emissivity results are much more scattering. This demonstrates that the RTHAT method under investigation is less affected by the target emissivity and more suitable for measuring target temperature without prior knowledge of emissivity.

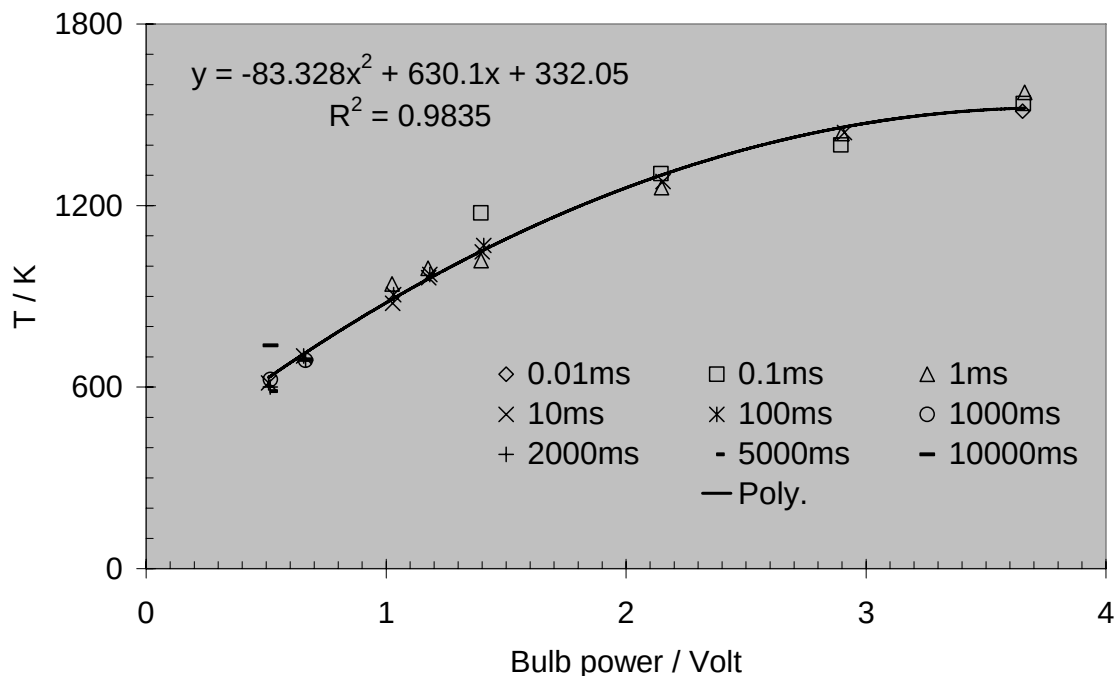


Figure 5.4(a) Bulb filament temperature versus power voltage. The spectrometer integration times are distinguished with different symbols.

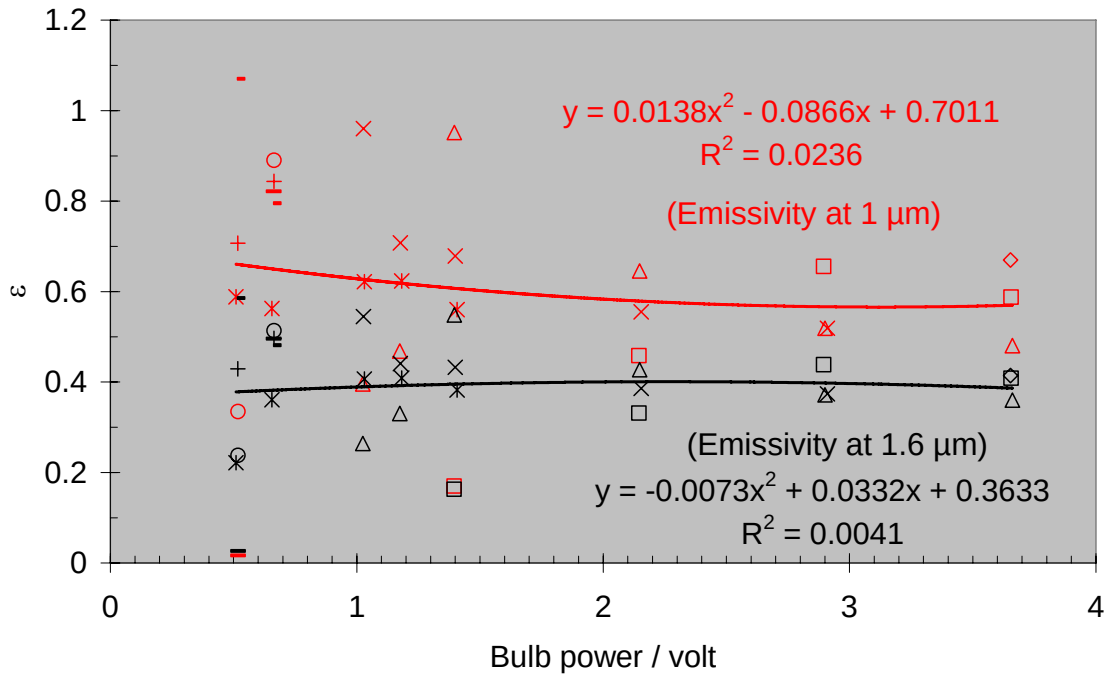


Figure 5.4(b) Bulb filament emissivity versus power voltage. The spectrometer integration times are distinguished with different symbols shown in (a).

Temperature and emissivity measurements of the blackbody cavity are made from the measurement signals presented in Figure 5.3(b). The RTHAT temperature measurements are compared with those by the type K thermocouple installed in the target, to demonstrate the effective correction of background radiation in the RTHAT temperature measurement. Temperature rises increasing with bulb radiation are observed in the RTHAT temperature measurements as shown in Figure 5.5(a). Those small temperature rises (< 9 K) can be attributed to the radiation heating of bulb light at the cavity surface. To test the consistency performance of apparatus, the RTHAT measurements were performed with two spectrometer integration times of 2 and 4 s respectively. The temperature variations due to the change of spectrometer integration time are small and within 1 K until the bulb voltage is higher than 3 volts. This measurement demonstrates that, in the investigated case, the effect of background radiation can be effectively corrected from the target signal in its temperature measurement using the RTHAT method.

The emissivity measurement of the black body cavity using RTHAT method is shown in Figure 5.5(b). As expected, without the bulb radiation, the measured cavity emissivity is very close to unity at both 1 and 1.6 μm wavelengths. However, the results show that the emissivity measurement was significantly affected by the bulb radiation when its voltage was above 2 volts. It was affected more at shorter wavelength of 1 μm than at 1.6 μm , probably because the radiation signal at shorter wavelength was more distorted by the bulb radiation.

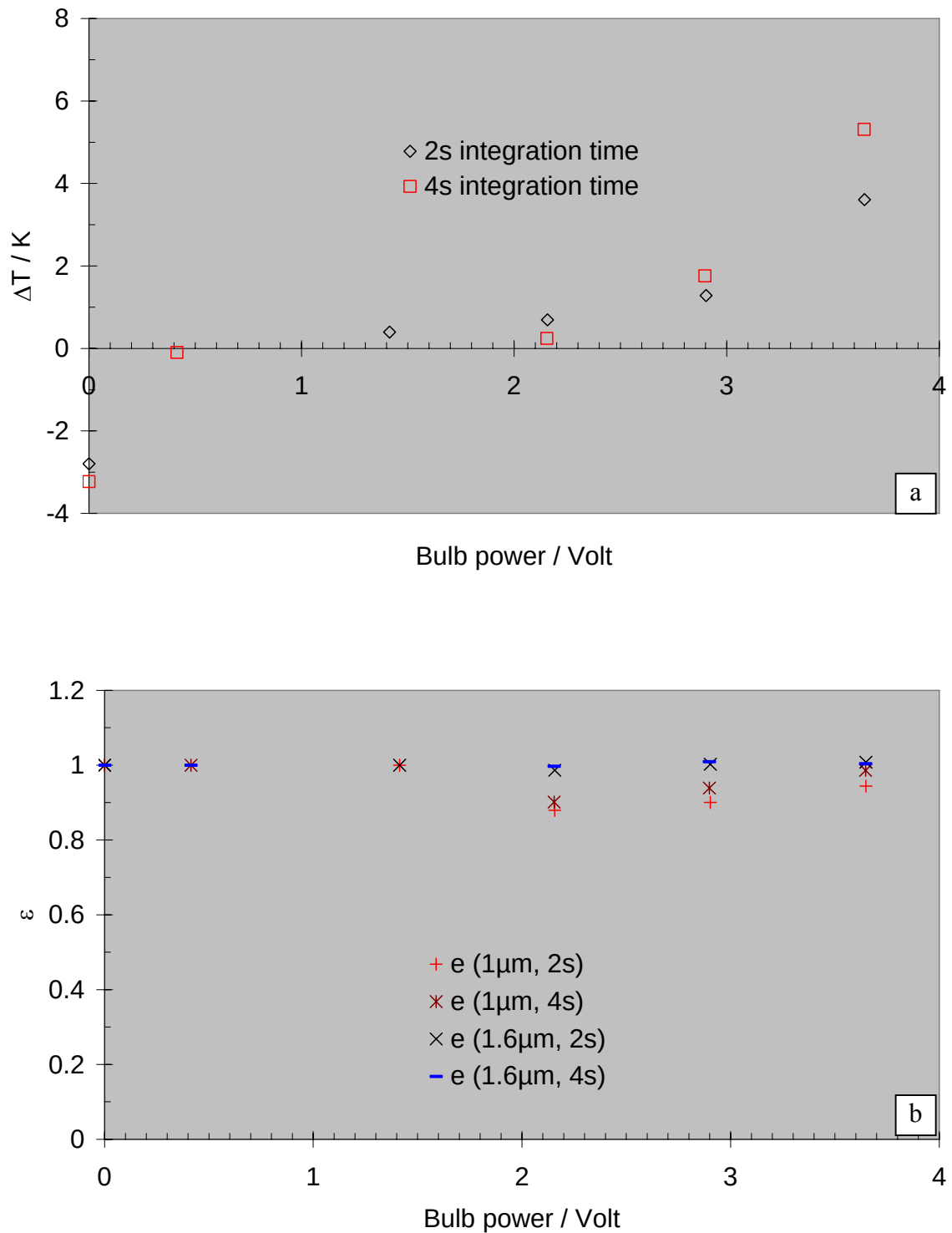


Figure 5.5 With the bulb radiation impinging on blackbody cavity surface, (a) differences between blackbody cavity temperatures measured by the RTHAT method and Inconel target temperatures measured by a type-K thermocouple (700.33 K) installed 0.5 mm behind the top Inconel surface and (b) RTHAT blackbody emissivity measurement versus bulb voltage.

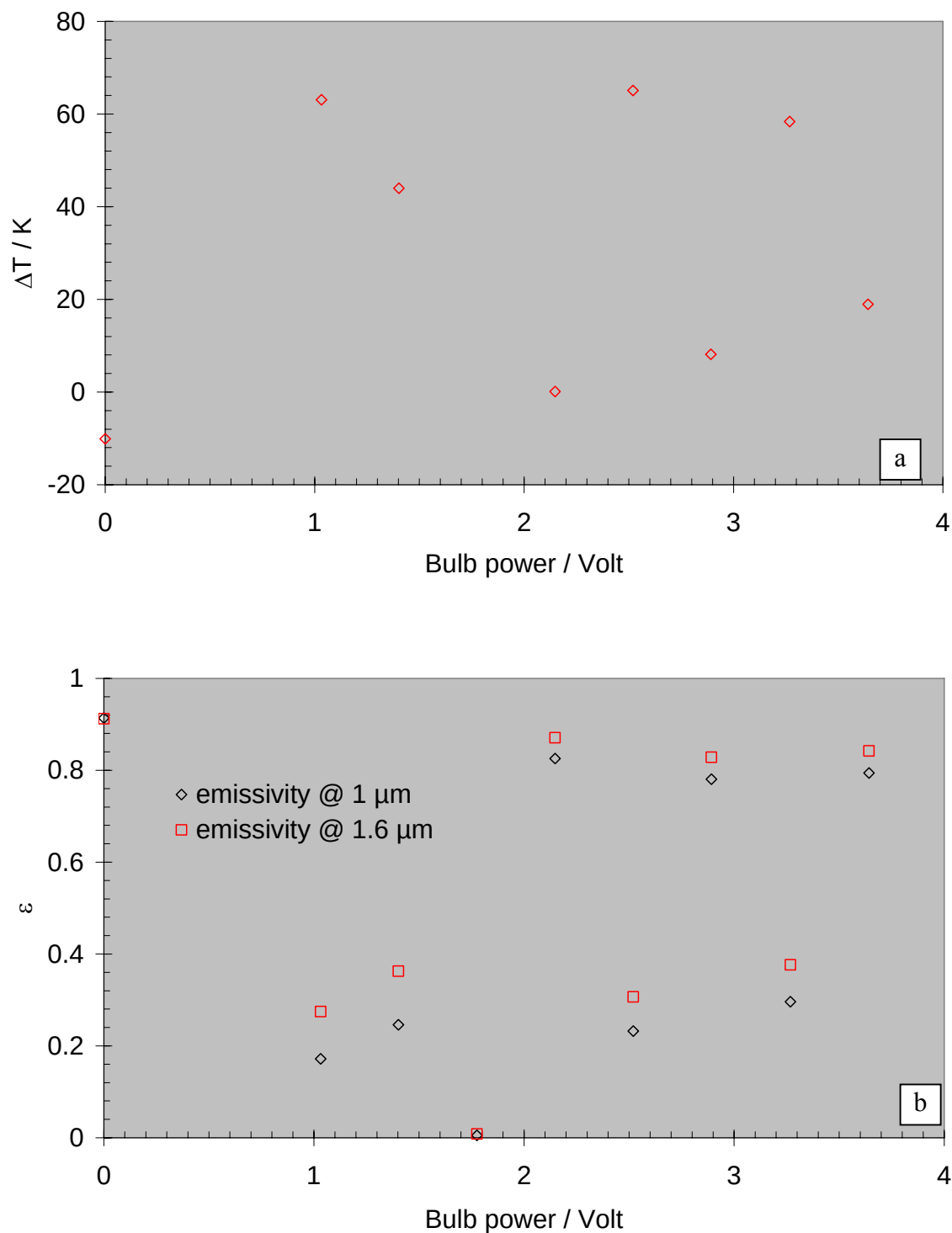


Figure 5.6 (a) Temperature differences versus bulb voltage between those measured from the Inconel surface by RTHAT method and by a type-K thermocouple (700.33 K) and (b) Inconel emissivity at 1 and 1.6 μm versus bulb voltage. The temperature difference at 1.776 volts is above 400 K and is not plotted out in the figure.

Inconel signal was more affected by the bulb radiation reflected at its surface as shown in Figure 5.3(c). Using the RTHAT method, the surface temperature has been computed and compared with that measured by the type-K thermocouple installed 0.5 mm under the Inconel surface. When the Inconel surface was not irradiated by the bulb radiation, there was a temperature difference of about 10 K between those measurements. This temperature difference can be explained by the temperature gradients caused by the thermal radiation heat loss at the Inconel surface.

When the Inconel surface was irradiated by the bulb radiation, it is noticed that the temperature differences between the RTHAT and thermocouple measurements, as shown in Figure 5.6(a), distinguishingly fall into two separate groups: one group $\Delta T > 40$ K and the other $\Delta T < 20$ K. When the Inconel emissivity at 1 and 1.6 μm wavelengths was calculated using RTHAT method, similar groupings also happen to the emissivity results, *i.e.* for one group $\varepsilon > 0.7$ and for the other $\varepsilon < 0.4$. From other sources of knowledge, it is known that the emissivity of oxidised Inconel at those wavelengths is greater than 0.5. Then the measurement data resulting in Inconel emissivity values below 0.4 can be disqualified. Once both temperature and emissivity results from the disqualified data omitted, it is interesting to find that only the results of lower temperature differences ($\Delta T < 20$) are left in Figure 5.6(a). The temperature rises increasing with bulb radiation intensity at the Inconel surface were probably due to the radiation heating by the bulb light.

The above analysis demonstrates that the emissivity measurement can be used to improve the temperature measurement using the RTHAT technique.

As shown in Figure 5.3(d), radiation signal from the platinum surface was severely distorted by the reflected bulb radiation. The temperature differences presented in Figure 5.7(a), between RTHAT measurements and those by the thermocouple increased rapidly with the bulb radiation. It is not surprising, since platinum is a difficult material for pyrometry temperature measurement due to its low emissivity and high reflectivity. The effect of severe contamination of reflected bulb radiation can also be found in the platinum emissivity calculations at 1 and 1.6 μm wavelengths in Figure 5.7(b). It was reasonable for the measured platinum emissivity to be just below 0.3 when there was no bulb radiation. However, with the bulb radiation, the measured platinum emissivity was untruly low (*i.e.* < 0.03), which was caused by the severe contamination of reflected bulb radiation in the platinum signal.

In summary, the RTHAT apparatus has been tested with an Inconel/platinum target with the light emitted by a bulb as the background radiation. The target surface temperature was about 700 K, determined by a type K thermocouple installed 0.5 mm behind the measured Inconel top surface. Using the RTHAT technique, a linear dependence of emissivity on wavelength was assumed and successfully applied in the computer model for the temperature and emissivity determination of bulb filament, blackbody cavity and Inconel surface. It is found the effect of reflected bulb radiation depends on both bulb radiation power and the target conditions. In this investigation, the temperature measurement of blackbody cavity was least affected and the error was less than 1% although the temperature of bulb filament was up to above 1500 K (determined by RTHAT measurement). For Inconel surface, the temperature error was within 3% when the emissivity measurement was used to help validate the temperature measurement. The error in the platinum temperature measurement was

unacceptably large (*e.g.* up to > 600 K) in this investigation and further improvements are needed.

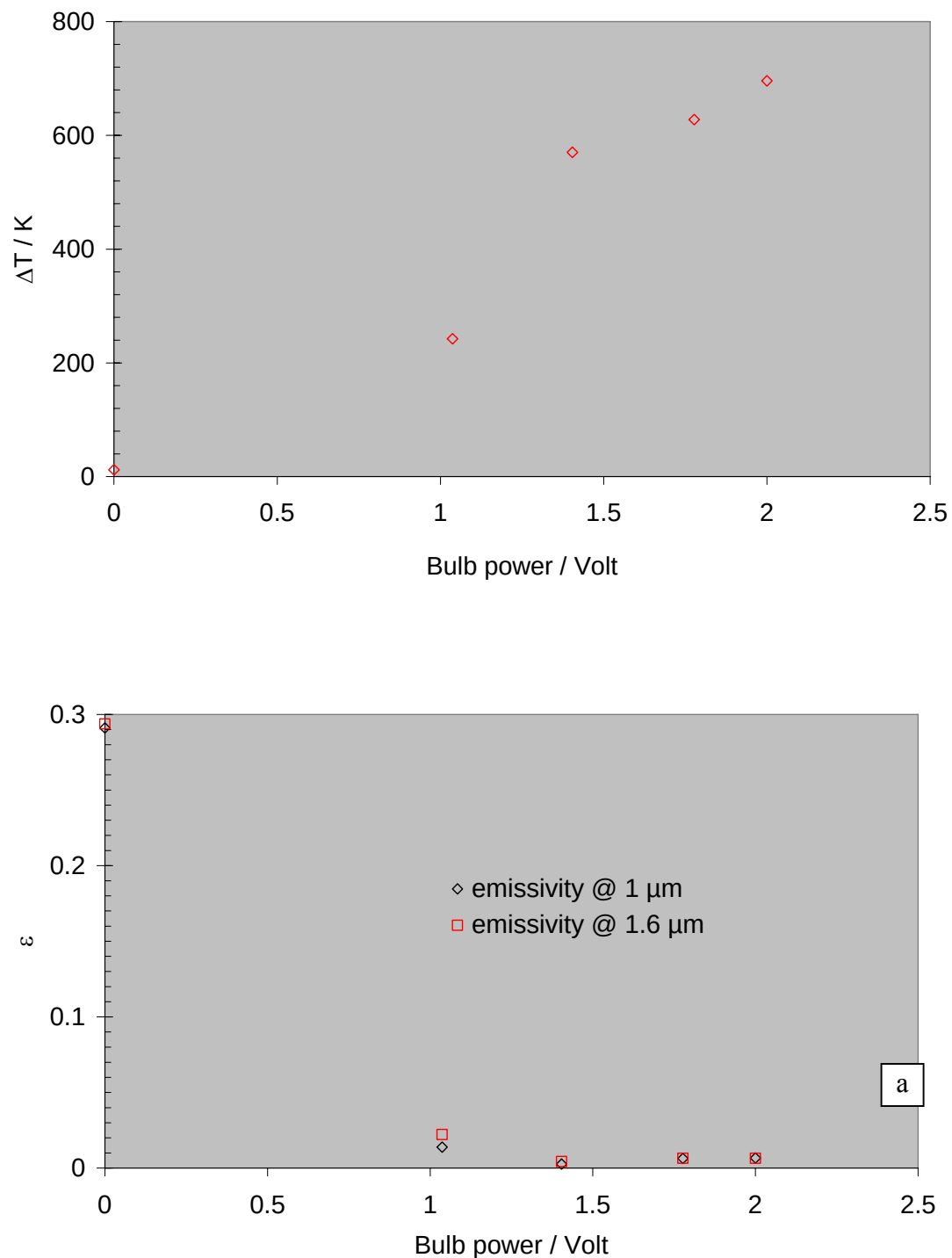


Figure 5.7 (a) Temperature differences versus bulb voltage between those measured from the platinum surface by RTHAT method and by a type-K thermocouple (700.33 K) and (b) platinum emissivity versus bulb voltage.

5.2 Test using NPL thermal shock rig

In order to apply the RTHAT apparatus to industrial applications over a wide range, a thermal shock rig, consisting of a modified Carbolite three-zone tube furnace, was used to test the apparatus. The rig also has a combustion system to produce a flame at the end of furnace, which can provide additional heating and temperature profile.

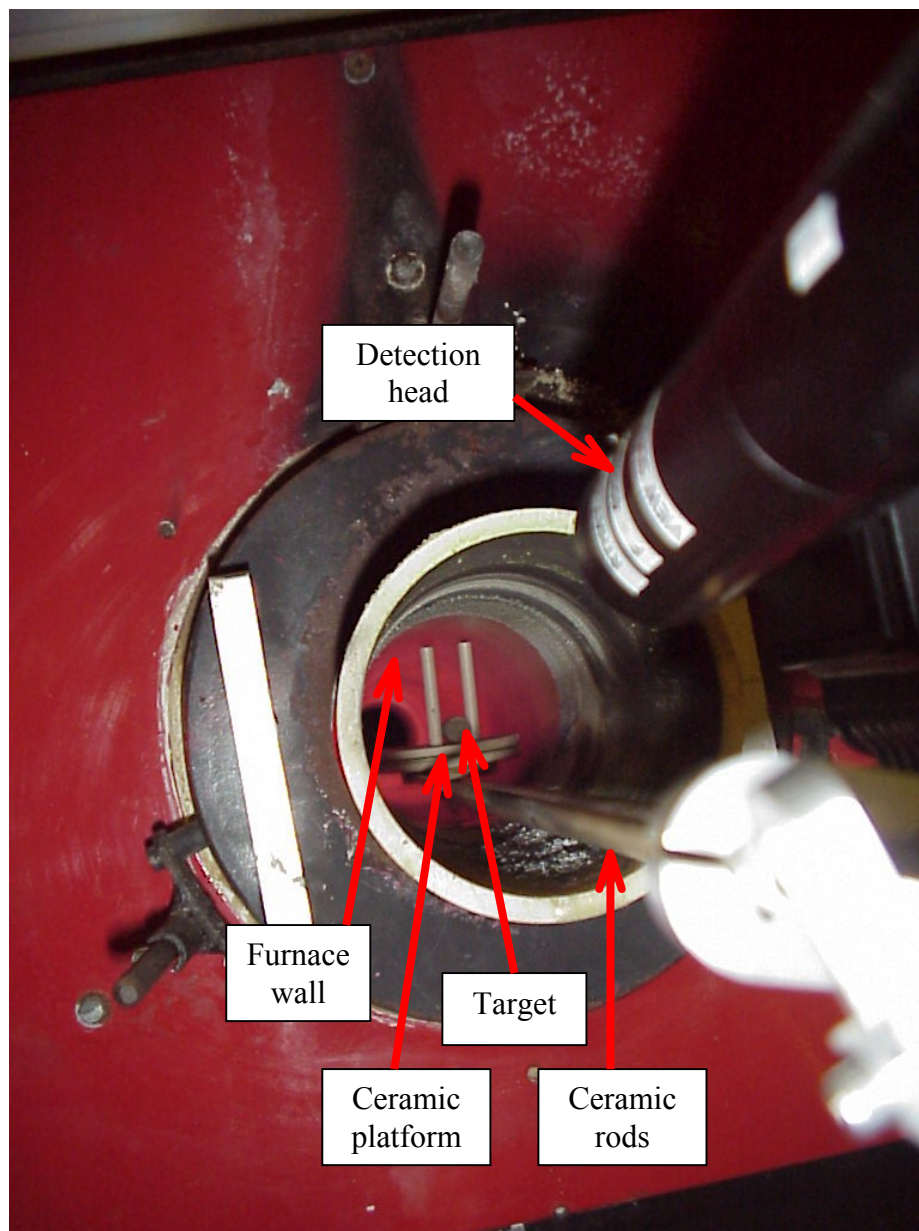


Figure 5.8 Photo of experimental set-up

As shown in Figures 5.8 and 5.9, a $\phi 10 \times 10$ mm oxidised Fecralloy rod target was placed on a 50 mm diameter ceramic disc and held in position by two ceramic bars. The disc was suspended and radiation heated inside the furnace using two long ceramic rods that can slide on a track to change the depth into the furnace. The temperature profile on the platform was checked using a type-R thermocouple probe that is made of $\phi 1$ mm Pt/Pt-Rh13% wires sheathed by a 5 mm OD twin-bore ceramic tubing.

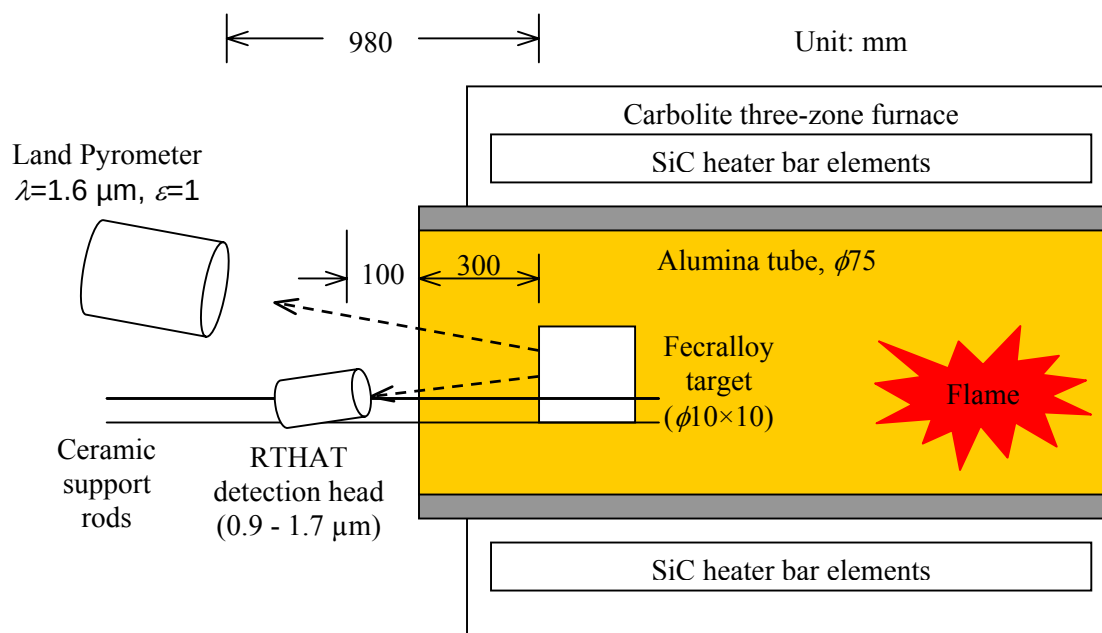


Figure 5.9 Block diagram of experimental set up (not to scale)

The rig uses a Eurotherm 2404 for background temperature control and a Eurotherm 2704 for furnace temperature control. During the measurement, the flame was produced by burning a gas of 0.7 bar kerosene/thiophene 5% in air. This gas flow rate was kept unchanged during the experiment.

The measurement was conducted at furnace temperatures of 750 and 950 °C with and without flame. Figures 5.10 and 5.11 show the temperature profiles measured in vicinities of target on the ceramic disc with and without flame. Although the positioning of the thermocouple probe was not precise, the measurements show that there were significant temperature gradients in the region of measurement. It can be seen that the temperature non-uniformity was larger at the lower furnace temperature of 750 °C, probably because of higher efficiency of radiation heat transfer at high temperature.

When the flame was on, the temperature inside the furnace increased significantly and the temperature profiles became more uniform, which was due to improved efficiency of heat exchange by combustion gases at high temperature.

Temperature profile with and without flame.

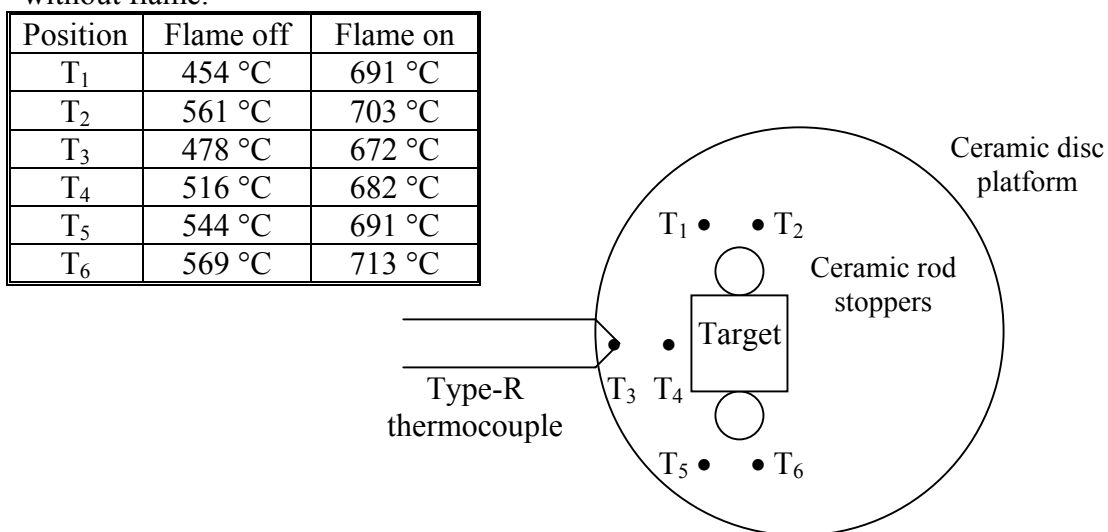


Figure 5.10 Temperature profile in vicinities of target on the ceramic sample platform, measured using a type-R thermocouple. The inset table shows the temperature measurements when the furnace was set to 750 °C, with and without flame.

Temperature profile with and without flame.

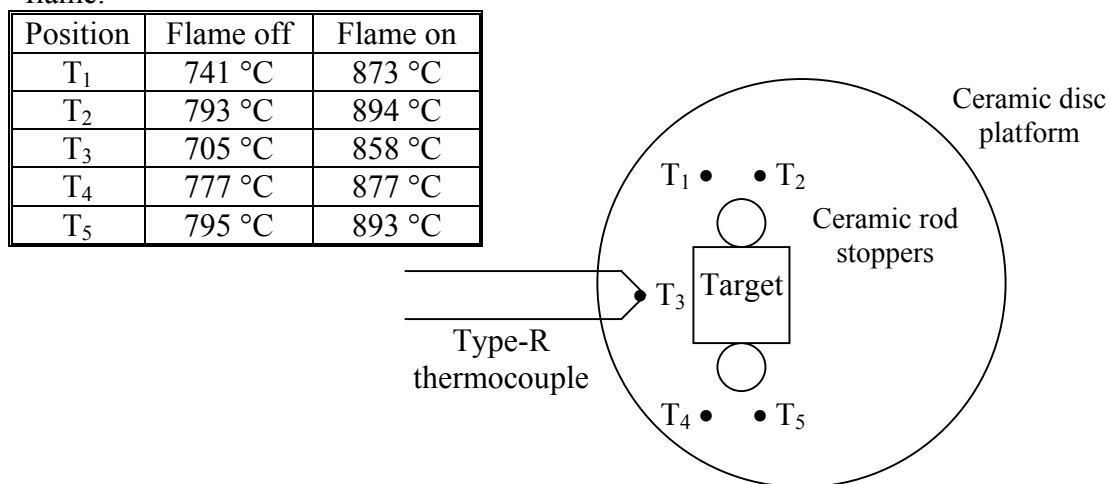


Figure 5.11 Temperature profile in vicinities of target on the ceramic sample platform, measured using a type-R thermocouple. The inset table shows the temperature measurements when the furnace was set to 950 °C, with and without flame.

In the experiment, radiation signals from both the target surface and furnace wall were measured. Then the reflected furnace radiation at the target surface was corrected in the calculations of the target temperature and emissivity using the RTHAT method outlined in Section 3.1. In the calculation, the signal-to-noise ratio (SNR) of measured signal was used as a weighting factor to improve the temperature measurement accuracy. For comparison, the temperature at different reference positions on the furnace wall was also calculated from their radiance signals. The results of the target temperature and emissivity are listed in Tables 5.1-5.4, and shown in Figure 5.12. For comparison, a Land pyrometer working at $1.6\ \mu\text{m}$ was also employed to measure the target temperature and the results are listed in Tables 5.3 and 5.4.

Table 5.1 Results of RTHAT temperature measurement when furnace was set to $T_{\text{fset}} = 750\ ^\circ\text{C}$ without flame

Reference position / cm	Temperature T / K			Emissivity ε		
	Target	Target (SNR weighted)	Wall	Target	Target (SNR weighted)	Wall
0	876.31	879.29	1022.39	0.812	0.681	0.633
3	829.31	880.93	1010.13	0.792	0.673	0.661
5	838.41	879.46	967.41	0.761	0.651	0.351
13	872.92	879.74	838.60	0.646	0.658	1.003
20	873.07	891.62	779.48	0.665	0.650	1.041
28	880.21	900.67	672.45	0.834	0.613	1.044
Average	861.71	885.29		0.752	0.654	
STD deviation / %	2.54	1.01		10.46	3.63	

Table 5.2 Results of RTHAT temperature measurement when furnace was set to $T_{\text{fset}} = 750\ ^\circ\text{C}$ with flame on

Reference position / cm	Temperature T / K			Emissivity ε		
	Target	Target (SNR weighted)	Wall	Target	Target (SNR weighted)	Wall
0	964.49	988.64	1025.44	0.839	0.731	0.666
5	969.16	985.03	1020.05	0.965	0.683	0.680
7	961.73	987.62	1046.44	1.001	0.678	0.417
Average	965.13	987.10		0.935	0.697	
STD deviation / %	0.39	0.19		9.11	4.17	

Table 5.3 Results of RTHAT temperature measurement when furnace was set to $T_{\text{fset}} = 950\text{ }^{\circ}\text{C}$ without flame

Reference position / cm	Temperature T / K			Emissivity ε		
	Target	Target (SNR weighted)	Wall	Target	Target (SNR weighted)	Wall
0	1063.27	1089.18	1201.27	0.840	0.683	0.787
6	1049.11	1094.93	1177.16	0.689	0.640	0.652
10	1064.76	1086.50	1169.27	0.652	0.690	0.510
15	1080.84	1097.50	1127.04	0.672	0.666	0.230
Average	1064.49	1092.03		0.713	0.670	
STD deviation / %	1.22	0.46		11.99	3.366	
Pyrometer	1103.10	1111.66		0.713	0.670	

Table 5.4 Results of RTHAT temperature measurement when furnace was set to $T_{\text{fset}} = 950\text{ }^{\circ}\text{C}$ with flame on

Reference position / cm	Temperature T / K			Emissivity ε		
	Target	Target (SNR weighted)	Wall	Target	Target (SNR weighted)	Wall
0	1166.49	1167.28	1234.63	0.842	0.663	0.816
5	1124.46	1172.46	1188.43	0.331	0.657	0.745
10	1150.31	1168.62	1192.39	0.463	0.670	0.539
15	1159.43	1172.06	1112.91	0.696	0.667	0.377
Average	1150.17	1170.10		0.583	0.664	
STD deviation / %	1.60	0.22		39.32	0.84	
Pyrometer	1211.21	1190.31		0.583	0.664	

The results show that the temperature on the furnace wall varied significantly over the investigated region. However the RTHAT determined target temperature was consistent when the detection position on the furnace wall for the reference signal was changed. It also shows that the standard deviation (STD) of the target temperature measurement was improved significantly when the signal-to-noise ratio of measured radiation signal was considered in the temperature calculation. It is noticed that the calculated furnace wall emissivity varied significantly, probably because of multiple radiation reflections among different parts of the wall, causing large errors in emissivity measurement particularly for regions where the wall temperature was

relatively low. As shown in Tables 5.3 and 5.4, temperatures measured by the pyrometer were consistently higher than those by RTHAT. This is because the reflected background radiation was not corrected in the pyrometer measurement.

The experiment was restricted by the 400 mm focal length of detection head. A new detection head with a focal length of 1000 mm has been built, and in the future, the target can be placed in a deeper position inside the furnace for the more uniform temperature profile.

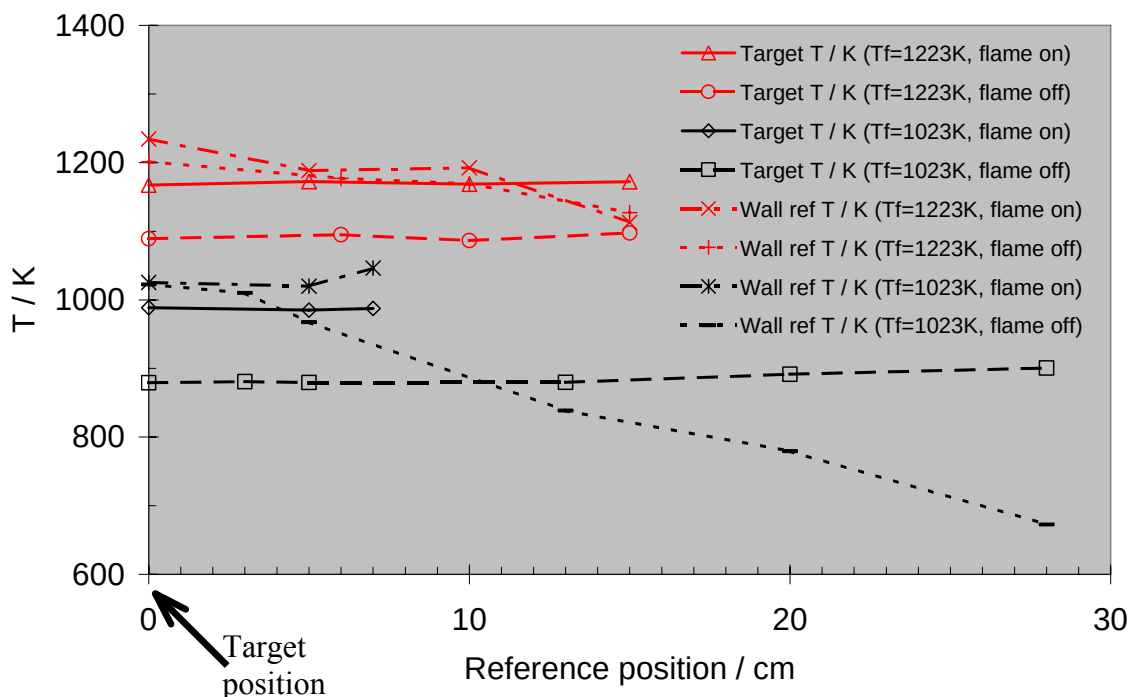


Figure 5.12 Temperature measurement of target and furnace wall using RTHAT apparatus

5.3 Test using a high temperature heat pipe

In the above two tests in Sections 5.1 and 5.2, it was impossible to directly compare the temperature measurements by the RTHAT method with those by other means. For the thermocouple measurement in Section 5.1, the temperature accuracy was limited by its spatial resolution and disturbance to the temperature field. For the pyrometer measurement in Section 5.2, the measurement accuracy was affected by the background radiation reflected at the target surface. For these reasons, a third test was designed in which a heat pipe was used for an uniform temperature field and a specially-designed Inconel target was used whose surface temperature can be accurately determined by thermocouple measurements. Then a direct comparison of temperature measurements by the RTHAT method and thermocouples can be made.

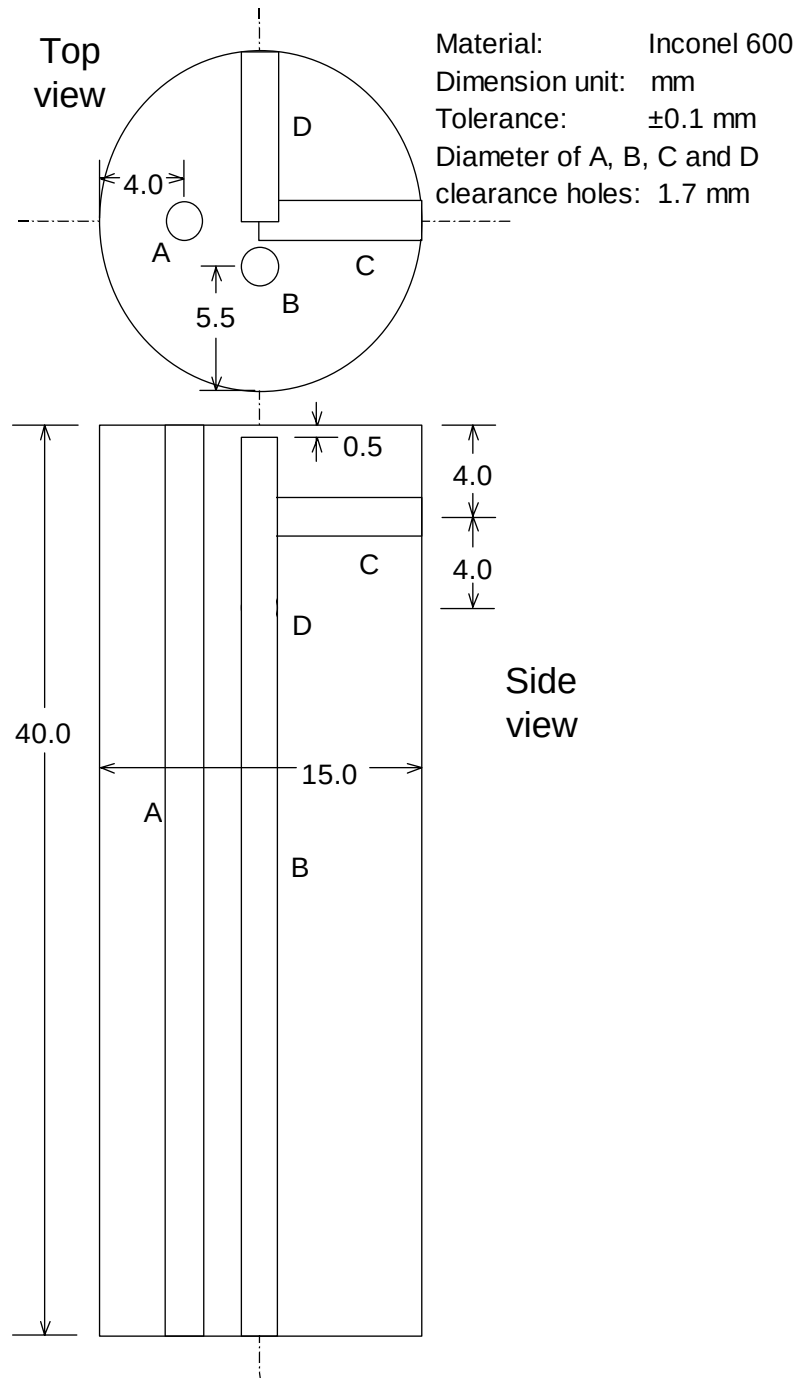


Figure 5.11 Sketch of Inconel target for test in heat pipe

The design diagram and photos of the Inconel target are shown in Figures 5.11 and 5.12. Four type-R thermocouples (indicated as A, B, C and D in the figure) made from calibrated $\phi 0.35$ mm Pt/Pt-13%Rh wires were used to determine target surface temperature in three ways for comparison. Thermocouple A is spot welded at the target surface to measure the surface temperature directly and thermocouple B is installed (0.5 mm) immediately under the surface. Thermocouples C and D are placed along the radial axis from side in distances of 4 and 8 mm respectively from the target surface to be measured. The target surface temperature is then calculated from the

temperature gradient measured by thermocouples C and D, on the basis of a linear temperature gradient assumption.

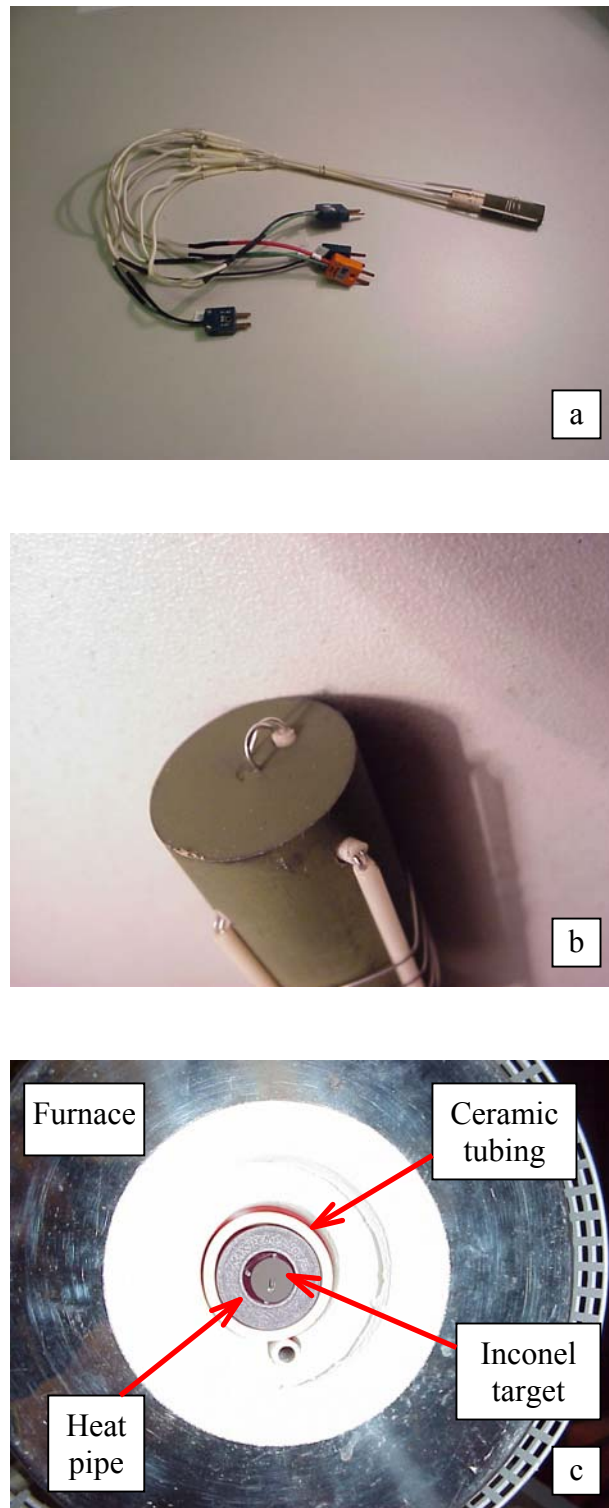


Figure 5.12 (a) Inconel target assembly (b) measured surface and, (c) inside heat pipe at 800 °C.

During the test, a Carbolite tube furnace (serial no. 6/95/1617) was used and a sodium heat pipe (also called isothermal furnace liner (IFL), Model: 11-YY-ZZ, serial no. ACT-0128, 18 mm ID, 36 mm OD and 210 mm long, supplied by Advanced Cooling Technologies, Inc., USA) was placed on a ceramic tubing concentrically inside the furnace as shown in Figure 5.12. The ceramic tubing separated the heat pipe from furnace heater wires and thus helped to achieve a highly isothermal temperature profile inside the heat pipe.

First, the heat pipe were blocked at its two ends using thermal insulation materials to achieve an isothermal condition in the central region where the target was placed. The target was heated in steps up to 900 °C, in order to oxidise and stabilise its surface conditions and also to check the performance of installed thermocouples. The result shows that the temperature differences among those thermocouples were within ± 0.5 °C for temperatures from 100 to 900 °C.

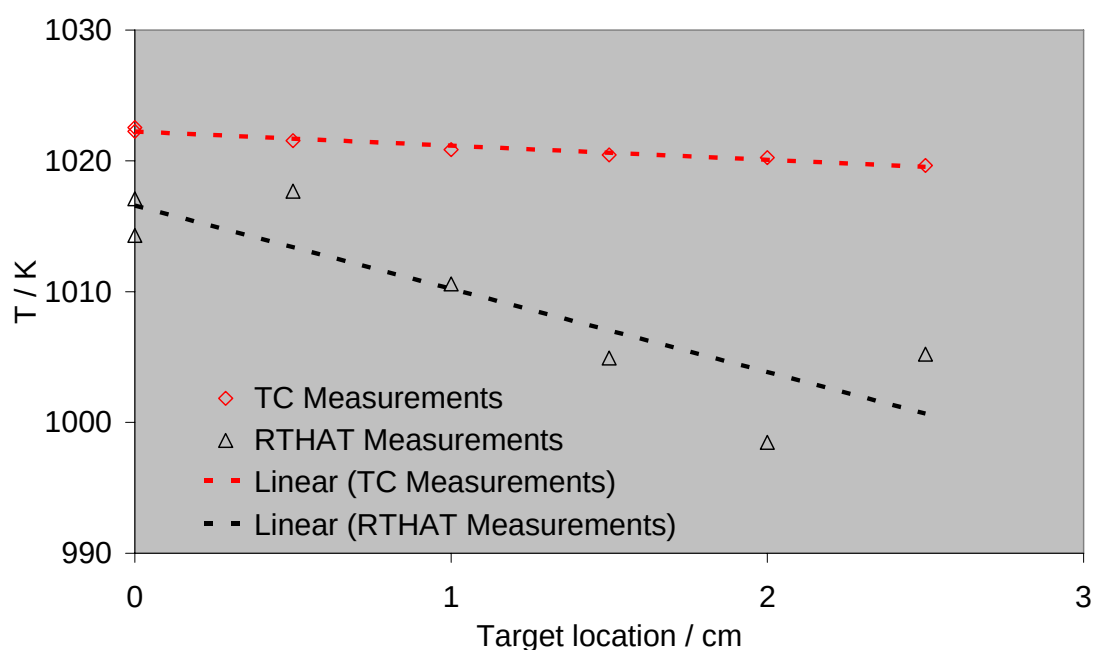


Figure 5.13 Temperature measurements of heat pipe end face vs target location inside the heat pipe. The temperature of end face outside heat pipe was measured using the RTHAT apparatus and the inside using a type-N thermocouple (TC). The linear fittings show the temperature decrease trends at heat pipe end when the target was moved into the heat pipe.

The test was performed when the target was placed in different depths inside the heat pipe with the furnace temperature set to 800 °C. A type-N thermocouple was used to monitor heat pipe temperature by inserting it into a small hole in the heat pipe wall to reach the other end face under investigation. Figure 5.13 shows the temperature measurements of the heat pipe end face using the RTHAT method and compared with those measured by the thermocouple. It is noticed that the temperature of heat pipe measured by the thermocouple decreased slightly but continuously when the target was pushed into the heat pipe. This temperature decrease up to 2.6 °C was probably

caused by the increase in radiation heat loss around the end of heat pipe as the target temperature increased and more inner wall area of heat pipe radiated towards outside when the target was located deeper inside heat pipe.

The end face temperature of heat pipe measured by the RTHAT apparatus was about 5 °C lower than that measured by the thermocouple inside when the target surface was in the same plain with the end face of heat pipe. This temperature difference increased gradually to about 22 °C when the target was pushed into the heat pipe by 2.0 cm, as shown in Figure 5.14. This can be interpreted by larger temperature gradients developed near the heat pipe end due to more radiation heat loss when the target was placed deeper inside the heat pipe. The departures from the linear trend of temperature difference in Figure 5.14 are probably due to the furnace power fluctuations, and uncertainties in temperature measurements by the RTHAT apparatus and thermocouples.

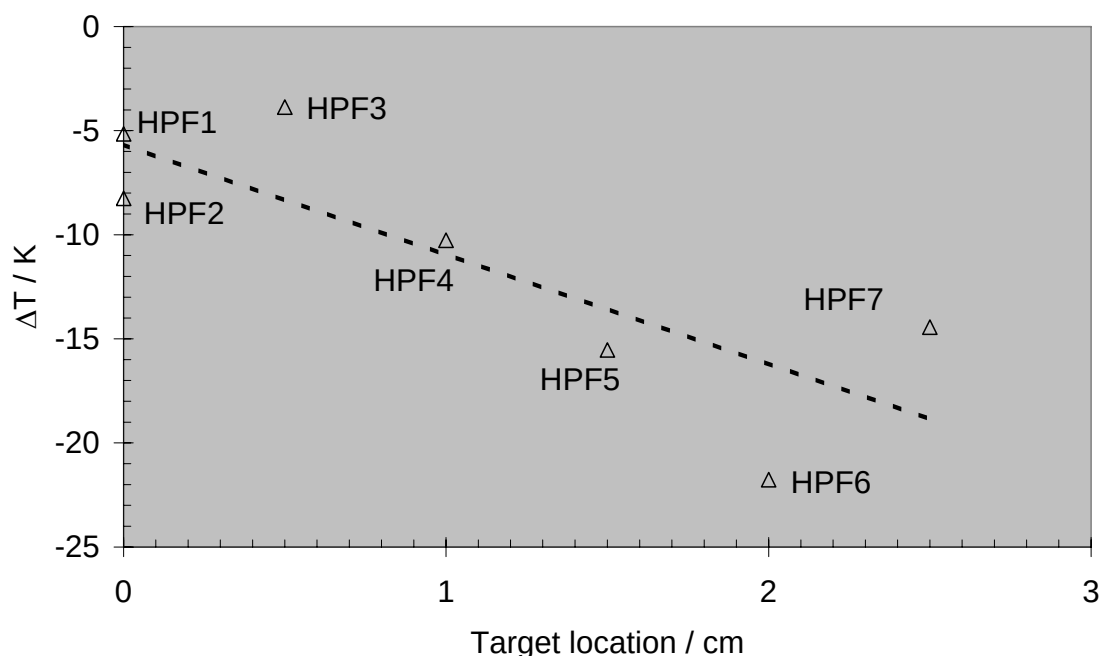


Figure 5.14 Temperature difference between two sides of heat pipe end measured by the RTHAT apparatus and a thermocouple as presented in Figure 5.13. The linear fitting shows the increase of the temperature difference when the target was moved into the heat pipe.

The surface temperature measurement of target was conducted and repeated at the same furnace temperature set to 800 °C, and compared with those by thermocouples, as shown in Figure 5.15. The thermocouple measurements show that the temperature profile inside the target was stable and repeatable. The higher temperature measured under the surface indicates the heat flux and temperature gradients caused by the radiation heat loss at the surface. The temperature differences among other three measurements are within 7 K, and the change in the RTHAT temperature

measurement is about 4 K (*i.e.* about 0.4%) representing the accuracy level of the RTHAT temperature measurement.

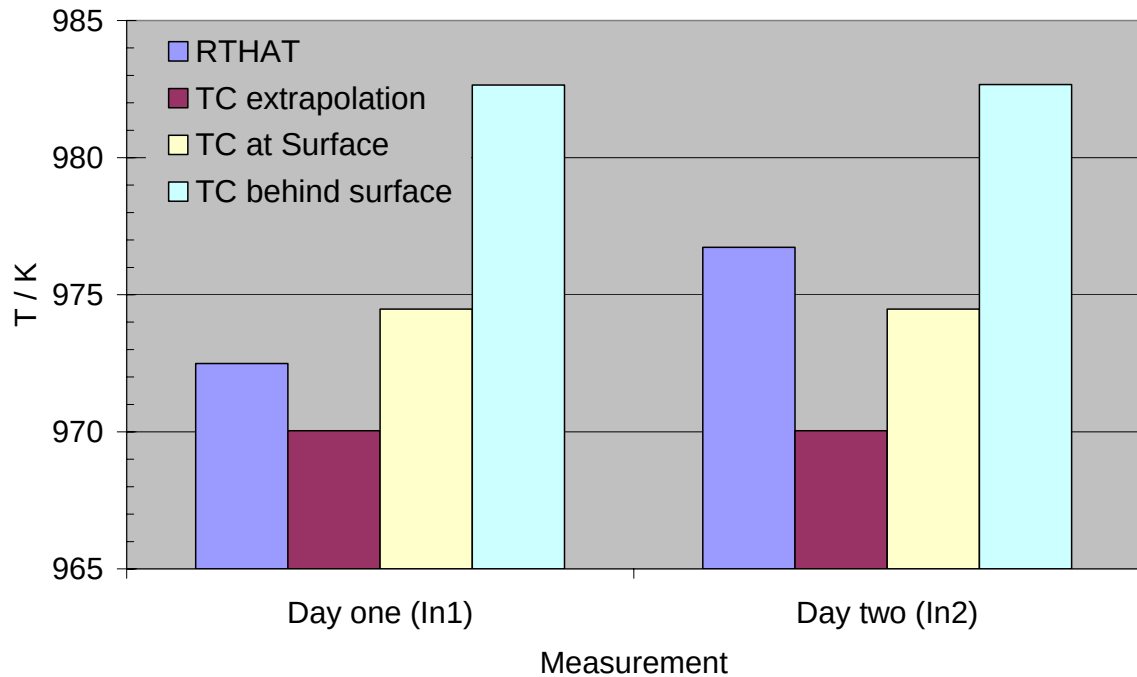


Figure 5.15 Two surface temperature measurements of Inconel target using the RTHAT apparatus performed separately on two successive days, and compared with those measured by type-R thermocouples.

In the RTHAT measurement, the emissivity of target can also be calculated as discussed in Sections 3 and 5.1.2. Figure 5.16 shows the emissivity spectra calculated from those measurements on the target face and the end face of heat pipe. Small variations are observed in the emissivity spectra of the end face of heat pipe, which may be caused by location changes of measured area on the end face. Similarly, there is an averaged change of about 3% in the measured emissivity spectra of Inconel target. Comparing this 3% emissivity change with the 0.4% change in the target temperature measurements discussed earlier, it shows that the temperature measurement is less sensitive than the emissivity to changes in target conditions using the RTHAT method.

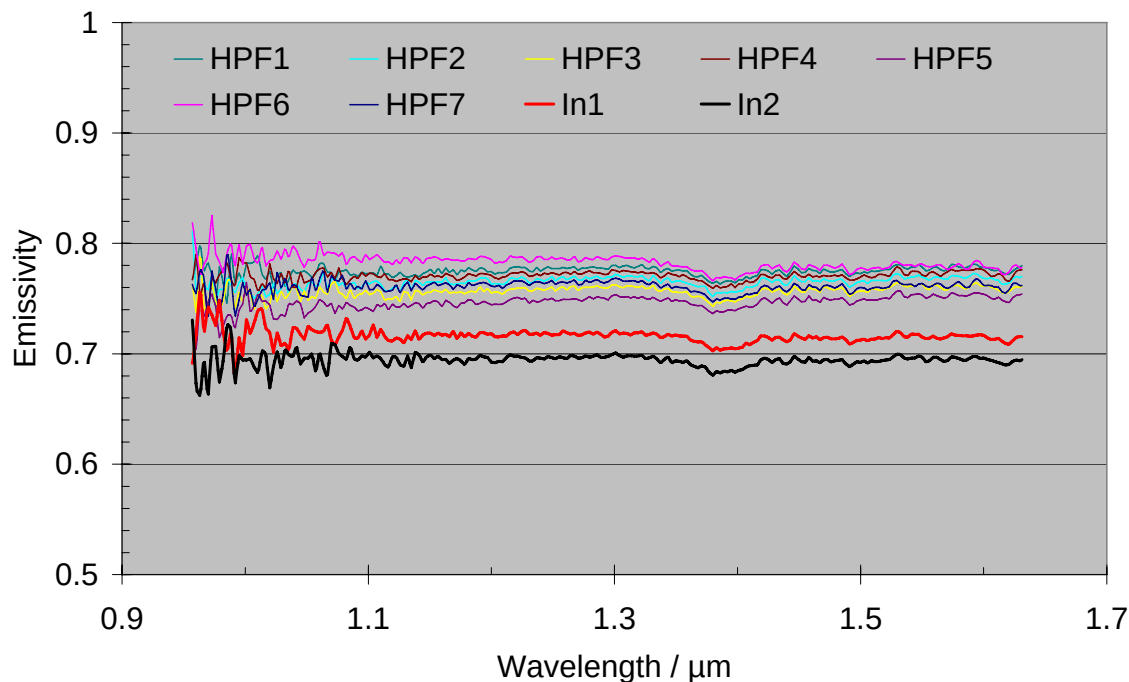


Figure 5.16 Emissivity measurements of heat pipe and Inconel target at 800°C. Corresponding temperature measurements can be identified according to labels in Figures 5.14 and 5.15.

6 Conclusion

In this work a spectral RTHAT technique has been investigated for accurate temperature measurement of targets in hostile environments where strong background radiation reflected at target surface can affect its temperature measurement severely using conventional radiation pyrometry techniques.

A portable spectral RTHAT apparatus has been built with use of an InGaAs spectrometer. The apparatus has been calibrated before it was tested in three experiments.

The theoretical modelling and experimental tests show that the RTHAT technique has potential to be developed into a unique technique for applications in industries, where distinctive signatures (*e.g.* absorption lines in gas combustion systems) in the background radiation spectrum can be exploited to effectively correct for its effect on the target signals.

The RTHAT model is based on the assumption that temperatures of target and its background are different, but both in isothermal conditions. However, in many industrial situations, the background is complicated by its complex geometrical structure, varying surface properties, and non-uniform temperature profiles. This makes its effective total radiation non-Planckian impinging at the target surface and the background radiation cannot be suitably represented by one measurement from

any area on the background surface. To effectively correct for the reflected background radiation for accurate temperature measurement in those difficult cases, reference radiation signals from different parts of the background can be taken in the RTHAT modelling. Also other auxiliary measures can be adopted. For instance, for the application of steel billet reheating inside a furnace, thermocouples may be installed to measure the temperature profiles on the furnace walls in addition to the investigation of their surface properties such as emissivity spectra and configuration factors to the billet to be treated. Then the background radiation impinging at the billet surface can be computed and compared with measurement to help improve the accuracy of the billet temperature measurement. In conclusion, the accuracy of temperature measurement by the RTHAT apparatus can be significantly improved if as much knowledge as possible of the system is exploited and the apparatus is designed to suit specific applications.

In the traditional pyrometry techniques, large errors in temperature measurement can be caused by poor knowledge of target emissivity or by failure in its wavelength dependence assumption. A conventional pyrometer usually measures radiance from a target at up to six wavelengths and relies on complex electronics to determine the target temperature. However, in a spectral RTHAT apparatus, the latest state-of-the-art spectrometer is employed, which is compact in size and can measure radiance over a wide spectrum simultaneously at high measurement speed. Powerful software and advanced computer technology make it possible for precise details of a system under investigation along with a large number (*e.g.* hundreds) of measured radiation signals to be considered. New methodologies in the data reduction can also be developed to improve the temperature measurement accuracy. For example, the signal-to-noise ratio (SNR) of signals can be used to optimise the determination of the target temperature. Using the curve-fitting techniques, unusual signal behaviours such as those caused by line absorption of gases can be identified and then under weighted or dismissed in the signal analysis.

The high speed of modern computer makes it easy to analyse data in the RTHAT measurement. Different polynomial assumptions of target emissivity can be easily tested to find the most accurate target temperature. The RTHAT technique has potential to be a powerful tool for non-contact temperature measurement of targets in hostile environments.

Acknowledgement: it is authors' pleasure to acknowledge the contribution of extensive discussions during the project, and critical comments on this report from Dr Gavin Sutton. They are also grateful to Helen McEvoy for her assistance in use of an NPL standard blackbody cavity in the calibration of RTHAT apparatus, and also to Steve Osgerby and Jim Bank for their help in use of a high temperature thermal shock rig in this work.

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