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The NPL InSb-based Radiation Thermometer for the Medium Temperature Range (< 962°C)

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Abstract Over the temperature range from 156 to 962°C, the NPL maintains a series of heatpipe blackbody sources for the calibration of customer sources, radiation thermometers, and thermal imagers. The temperature of each of the sources is determined using a calibrated platinum resistance thermometer or gold-platinum thermocouple placed close to the radiating surface at the back of the cavity. The integrity of such a blackbody source relies on it having good temperature uniformity, a high and well-known effective emissivity, and having the sensor in good thermal contact with the cavity. To verify the performance of the blackbody sources, it is necessary to use an infrared thermometer that has been independently calibrated to compare the radiance temperature of the source with the temperature measured by the contact sensor. Such verification of the NPL blackbodies has been carried out at short wavelengths: from 500 to 1,000°C using the NPL LP2 calibrated using the NPL gold point, and at 1.6 μm using an InGaAs-based radiation thermometer calibrated at a series of fixed-points from indium (156°C) to silver (962°C). Thermal imaging systems traditionally operate over the 3–5 μm waveband and are calibrated using NPL sources. Up until now, it has not been possible to verify the performance of the sources in this waveband except indirectly by cross-comparison of the sources where they overlap in temperature. A mid-infrared (nominally 3–5 μm) radiation thermometer has, therefore, been designed, constructed, and validated at NPL. The instrument was validated and calibrated using the fixed-point blackbody sources and then used to validate the heatpipe

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blackbodies over their temperature range of operation. The results of the instrument validation and blackbody measurements are given.

Keywords Blackbody source · Infrared thermometer · InSb

1 Introduction

Over the temperature range from −40 to 3,000°C, the National Physical Laboratory (NPL), UK, maintains and disseminates the International Temperature Scale of 1990 (ITS-90) for the benefit of users and manufacturers of blackbody sources and radiation thermometers, including infrared ear thermometers and thermal imagers. Above typically 1,000°C, the scale is disseminated by means of a high temperature, graphite blackbody source and a characterized precision, linear pyrometer (LP2), operating at either 650 or 906 nm and calibrated with reference to a blackbody source at the gold freezing point (1,064.18°C). Between −40 and 1,000°C, calibrations are performed at wavelengths up to 14 μm using a number of heatpipe blackbody sources: ammonia (NH_3) (−40 to +50°C), water (H_2O) (+50–250°C), cesium (Cs) (300–600°C), and sodium (Na) (500–1,000°C) [1,2]. These consist of a cylindrical blackbody constructed within the heatpipe and are contained either in a metal jacket for circulation of a chilled fluid for temperature control (in the case of the ammonia heatpipe) or within an electrically heated furnace. The temperature of each blackbody is determined by a calibrated contact sensor, either a platinum resistance thermometer or thermocouple, held in close thermal contact with the back wall of the cavity. To be effective as reference sources, the cavity must be isothermal, with a high and known emissivity over the range of wavelengths of use. In addition, the contact probe, giving traceability to the ITS-90, must be in good thermal contact with the back wall of the blackbody to represent accurately the cavity temperature.

It is advantageous to have some means of verifying the performance of the sources by using an independently calibrated radiation thermometer to compare the radiance and contact probe temperatures. Previously, this has been achieved from 500 to 1,000°C using the LP2, and from 150 to 1,000°C using an InGaAs thermometer, operating at nominally 1.6 μm [3–5]. The latter was calibrated using a series of fixed-point blackbody sources from indium (In, 156.599°C) to silver (Ag, 961.78°C), and the results were fitted using a Sakuma–Hattori type function. It was then used to measure the radiance temperature of the heatpipe blackbody sources at a number of temperatures over their range and the results compared to the temperature measured by the contact probe. Both of these validations were at relatively short wavelengths. The only way of checking the operation of the sources at longer wavelengths was to cross-compare two sources in the temperature range of overlap using a transfer radiation thermometer operating at the wavelength of interest. However, validation is very limited because there is very little range of overlap between the sources, namely, for the Cs and Na sources from 500 to 600°C and the H_2O and NH_3 sources at only 50°C.

An InSb-based radiation thermometer operating over 3–5 μm and designed to be calibrated using fixed-point blackbody sources has been constructed. The instrument

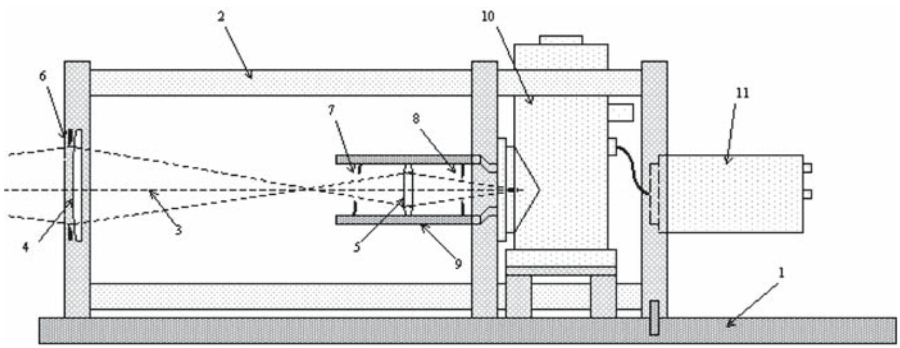

Fig. 1 Schematic diagram of the design of the Mark II InSb thermometer 1. anodized Al breadboard; 2. Invar rods; 3. optical axis; 4.objective lens, 50.8 mm diameter; 5. focusing lens, 31.5 mm diameter; 6. anodized Al objective stop, 40 mm diameter; 7. anodized Al angled field stop, 900 μm diameter; 8. anodized Al Lyot stop, 5 mm diameter; 9. anodized Al lens tube, temperature controlled; 10. cooled InSb detector and filter in Dewar (77 K); 11. trans-impedance amplifier, temperature controlled

(designated Mark II) complements the 4 μm InSb device for higher temperatures (Mark I), described elsewhere in these proceedings [6].

2 Design and Construction of the Thermometer

2.1 Optical Design

2.1.1 Rationale

The thermometer was required to (i) have a small target size at a suitable working distance so it could be calibrated using fixed-point blackbody sources that have a nominally 9 mm diameter aperture; (ii) have a low size-of-source effect (SSE); (iii) operate over the mid-infrared range (∼3–5 μm); and (iv) have sufficient sensitivity to enable it to cover the temperature range from 150 to 962°C, i.e., over as much of the heatpipe operating range as possible. These requirements were taken into account during the design and construction of the instrument.

2.1.2 Optical Design and Construction

Figure 1 gives a schematic diagram showing the design of the thermometer. An indium antimonide (InSb) detector with a 4 mm active area is mounted into a vacuum Dewar and cooled with liquid nitrogen during use. The Dewar window is broadband (1–6 μm) anti-reflection coated sapphire. The interference filter (of nominally 3–5 μm bandwidth with a rejection notch at 4.05–4.5 μm to block out the atmospheric absorption band at these wavelengths) is also mounted in the vacuum Dewar along with a field-of-view limiting aperture. A second (uncooled) short pass filter extends the out-of-band blocking to remove a humidity sensitivity that was thought to be caused by a long wavelength water absorption band that just falls within the detection range of the system. The output from the detector passes, via an amplifier, to a digital voltmeter. The amplifier is temperature controlled at ∼30°C.

The optical layout of the thermometer was designed using the optical ray-tracing software Zemax ©. The configuration and design were chosen to minimize the effect of stray radiation and scattering within the instrument and to improve the SSE. The field-of-view of the thermometer was required to be nominally 3 mm at a suitable working distance from the source.

An aperture stop is placed in front of the objective lens. The objective lens focuses the image onto the field stop, which is angled at approximately 8° to the perpendicular of the optical axis to minimize back reflections from the stop onto the objective lens. A second lens refocuses the image onto the detector's active area. A third aperture stop, the glare or Lyot stop, is positioned between this second lens and the detector where the secondary lens images the aperture at the objective. Silicon lenses were chosen due to the low temperature coefficient of silicon, and the lenses were anti-reflection coated. The stops are constructed from black anodized aluminum. Further, to improve the stability of the thermometer, the focusing lens, objective stop, and Lyot stop are contained in a black-anodized aluminum lens tube which is temperature controlled at ∼ 30°C.

2.2 Mechanical Construction

Mechanical stability of the thermometer is achieved by mounting the components onto Invar rods. The Invar rods are painted with a high emissivity black paint to reduce scattering and reflections. The entire assembly is then mounted onto a black-anodized breadboard. A foam-insulated casing surrounds the instrument to eliminate the entry of stray light and also to provide thermal insulation and improve the temperature stability.

The background signal of the instrument is determined by using a low-speed chopper mounted inside the thermometer casing. Software controls the chopper and records the thermometer output. The software automatically deducts the background measurement from the signal when the thermometer is viewing the source. To aid the alignment of the thermometer onto the source, a cross-hair laser system on a four-axis precision mount is mounted onto the breadboard to one side of the thermometer.

3 Evaluation Measurements for the Instrument

3.1 Optimum Focal Distance and Size-of-Source Effect

The optimum focal distance and SSE of the thermometer were determined using a large-area heatpipe blackbody source and a range of aperture plates of different diameters mounted onto a water-cooled aperture plate in front of the blackbody. The optimum focal distance was determined by scanning the thermometer across a small aperture at a number of different distances from the source and finding the distance that corresponded to the sharpest scan profile and highest thermometer signal when

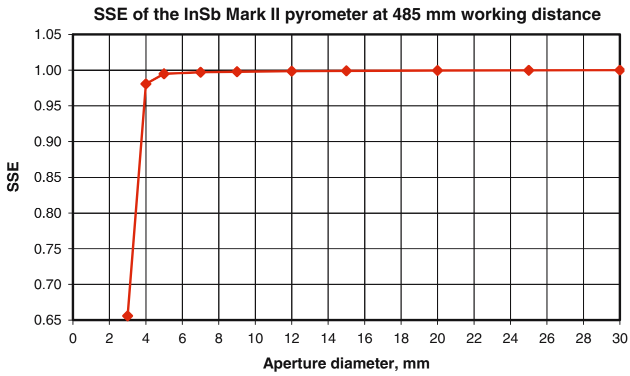

Fig. 2 Plot of the SSE results at the optimum working distance of 485 mm

aligned on the aperture. These measurements were confirmed by performing SSE measurements at different distances using the "direct method". The optimum working distance was found to be nominally 485 mm, as measured from the front of the thermometer casing to the blackbody aperture. The SSE measurements at this distance are given in Fig. 2 showing the ratios of the output at each aperture diameter to that at the maximum 30 mm diameter aperture. The results show that, at 3 mm diameter, the SSE ratio is 0.655, but the SSE curve rises sharply and is then larger than 0.99 for apertures of 5 mm and above. These results confirm the suitability of the instrument for use with the 9-mm-diameter aperture fixed-point sources.

3.2 Fixed-point Measurements

The thermometer was calibrated using fixed-point blackbody sources at the indium (In, 156.5985°C), tin (Sn, 231.928°C), zinc (Zn, 419.527°C), aluminum (Al, 660.323°C), and silver (Ag, 961.78°C) points. These have been described previously [3,4]. The estimated effective emissivity of the fixed-point cavity is 0.9999. In order to realize the fixed points, the blackbody assemblies are contained centrally inside a three-zone electrically heated furnace within a silica work tube. In this arrangement, the distance from the blackbody aperture to the front end of the work tube is approximately 342 mm. Since the working distance of the thermometer is nominally 485 mm, this means that the front of the thermometer is close ($<$145 mm) to the front of the work tube.

Measurements of both the melting and freezing points of all the fixed points were performed. Profiles for the In and Ag points are given in Figs. 3 and 4, respectively. The range of the instrument was such that it was possible to perform all the measurements using one amplifier gain setting. The thermometer had sufficient sensitivity for measurements down to 150°C, with the standard deviation on a typical plateau being $<$ 0.05°C. However, the output from the thermometer decreases steadily over the day when viewing the fixed point. This decrease is very apparent at the higher temperatures (Al and Ag) and can be clearly seen in the plot of the Ag-point profiles.

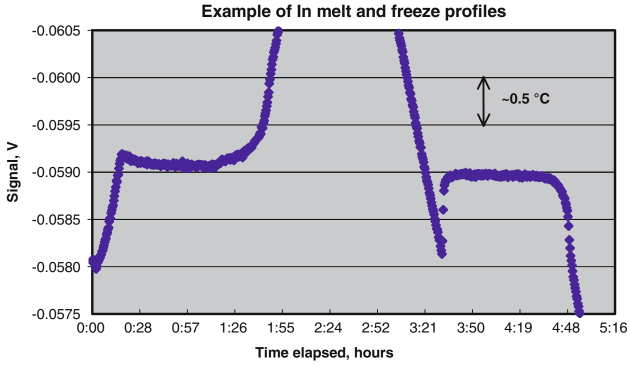

Fig. 3 Plot of the melting and freezing plateaux for the In fixed point

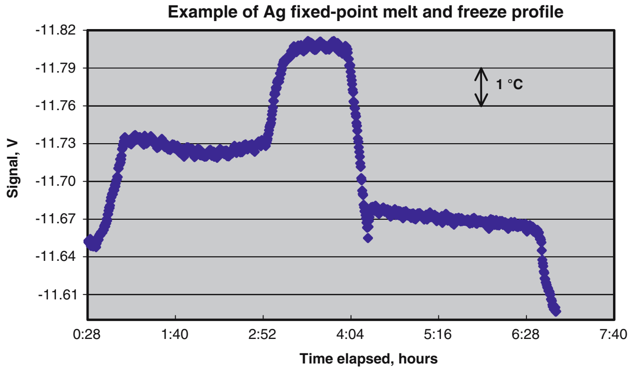

Fig. 4 Plot of the melting and freezing plateaux for the Ag fixed point

This drift results in the average output during the fixed-point freeze being consistently lower than the output during the previous melt, by a large amount in the case of the Ag point, and is assumed to be due to the close proximity of the thermometer to the front of the furnace, leading to the gradual warming of the thermometer components over the day.

The average of the thermometer output, including the melt and the freeze, was calculated for each fixed point. In order to assess the operation of the thermometer, a least-squares fit of the results was performed using a version of the Planck form of the Sakuma–Hattori interpolation equation [7];

$$V(T) = \frac{a_1}{\exp(c_2/(a_2T + a_3)) - 1} \tag{1}$$

where $V(T)$ is the output voltage of the thermometer, T is the temperature in kelvin, c_2 is the second radiation constant, and a_1, a_2, and a_3 are constants.

The rms residual of the fit using data from all five fixed points was 0.7°C. This is somewhat larger than is ideal and is possibly caused by the drift at the higher temperatures. To evaluate the effect of the drift, and to try and provide a better fit, further fits were performed using four points (eliminating the Ag point results) and three points (using the In, Sn, and Zn point results only). The former yielded an rms residual of 0.5°C.

3.3 Stability Evaluation

The medium term stability of the thermometer was assessed by repeating the Al point measurements after a period of approximately two months. The average thermometer output of the second series of measurements agreed with that of the first series to within the equivalent of 0.1°C, which is within the observed repeatability of the measurements.

4 Measurements with the NPL Heatpipe Blackbody Sources

The main purpose in building the thermometer was to evaluate the NPL variable temperature heatpipe blackbody sources. Therefore, in order to assess the feasibility of this, some measurements were made at a number of temperatures from 150 to 960°C using the NPL H_2O, Cs, and Na heatpipe sources. Since the results of the fit were less than ideal, the temperatures were chosen to be close to the fixed-point temperatures, i.e., at nominally 150, 230, 420, 660, and 960°C. So far, only some preliminary measurements have been carried out with the heatpipe sources.

The H_2O and Cs sources have been described previously [2,3]. Recently, the NPL purchased a new Na heatpipe source. This is constructed from oxidized Inconel. The blackbody cavity is of the same design as the H_2O and Cs heatpipes, but the overall length of the heatpipe is longer to give sufficient immersion depth for the calibrated Au/Pt thermocouple that is used as the contact sensor within the source.

The effective diameter of the Ag and Sn fixed-point sources was estimated using the results of the SSE measurements and thermal profile scans across the sources, and found to be nominally 30 mm. Therefore, to minimize any residual effects due to SSE, the aperture diameter of each heatpipe source was also set to 30 mm using water-cooled, blackened aperture plates. For these initial evaluation measurements, no additional SSE correction was applied to the results to allow for any difference in the thermal profiles of the fixed-point and heatpipe sources.

For each series of measurements, the output of the thermometer was recorded along with the temperature, t_{90}, derived from the output of the contact probe within the heatpipe source. The coefficients of the fit were used to calculate the radiance temperature from the thermometer output. Since the heatpipe measurements had been made at temperatures close to the fixed points, it was possible to compensate somewhat for the relatively poor fit by using the residuals at the appropriate fixed-point temperature to correct the radiance temperature. A correction to take into account the emissivity of the heatpipe sources was also made.

The results of the preliminary heatpipe evaluation measurements are given in Table 1. The estimated $k = 2$ measurement uncertainties include: (i) the uncertainty in realizing the fixed point, including stability of the measurements, the residuals of the fit, and the effect of emissivity; and (ii) the uncertainty for the heatpipe source,

Table 1 Summary of the measurement results with the heatpipe blackbody sources

Heatpipe source	Nominal temperature (°C)	Temperature as measured by the InSb thermometer, t_{rad} (°C)	Temperature from contact sensor, t_{90} (°C)	Difference (t_{rad}–t_{90}) (°C)	Estimated uncertainty ($k = 2$) (°C)
Na	955	954.5	954.9	−0.4	1.0
Na	660	657.9	658.9	−1.0	0.7
Cs	420	419.9	421.3	−1.4	0.3
H_2O	225	224.9	225.4	−0.5	0.1
H_2O	153	152.5	153.0	−0.5	0.2

including the calibration of the contact sensor and the effect of the emissivity, and the stability and reproducibility of the measurements.

5 Discussion

The results of the SSE and medium-term stability checks were good, and the measurements with the blackbody sources show that the thermometer has sufficient sensitivity and range for use, from at least the In point up to the Ag point. The thermometer therefore shows good potential to be suitable for the purpose for which it was designed. However, the performance is currently limited due to the drift of the output during the day. This drift is likely to be due to the gradual warming of the components as it is more evident when used with the higher-temperature fixed points. At lower temperatures and when using the heatpipe sources, the drift is less significant. The results of the measurements with the heatpipe sources presented here show differences between the radiance and thermocouple temperatures that are larger than the estimated measurement uncertainties, probably due to the thermometer drift, and the results should therefore be treated as provisional. It is intended that further measurements will be carried out and steps taken to reduce the drift, for example, by using a different front lens to increase the working distance of the thermometer.

6 Conclusion

An InSb-based radiation thermometer operating over the wavelength band from 3 to 5 μm has been designed, constructed, and validated. Preliminary results show that the thermometer has good potential. It is hoped that with further investigations and modifications, the issues surrounding the short-term drift of the instrument will be overcome and its performance enhanced. This should hopefully result in a better fit using the Sakuma–Hattori equation, and enable the instrument to be useable throughout its operating temperature range. It will then be an extremely useful tool for evaluating the NPL heatpipe blackbody sources.

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