NON-CONTACT TRUE TEMPERATURE MEASUREMENTS IN THE MICROGRAVITY ENVIRONMENT

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INTRODUCTION

The accurate measurement and control of temperature can be of great importance in most materials manufacturing and processing applications. With present-day technology such measurement almost always requires either physical contact with the subject or an extensive calibration procedure. In many cases contact is either not desirable, because such contact may significantly alter the temperature or other characteristics of the subject, or is not possible because the subject is moving, is too far away, is too hot or is in an otherwise hostile environment. Similarly calibration may not be possible if the characteristics change too much.

Multiwavelength pyrometry can help solve some of these problems by providing a reliable method for emissivity independent noncontact true temperature measurements.

BASIC THEORY

All bodies above absolute zero radiate thermal energy. The most efficient thermal radiator is a black body, which is defined as an object that will absorb all incident radiation. The emitted radiance per unit wavelength or spectral radiance of such a body is given by the Planck radiation law:

$$N'_\lambda = C_1 \lambda^{-5} (\exp(C_2/\lambda T) - 1)^{-1} \quad (1)$$

where λ is the wavelength, T is the absolute temperature and C_1 and C_2 are the Planck constants. Figure 1 is a plot of N'_λ vs. λ at various temperatures. The dotted curve depicts Wiens law (as opposed to Wiens approximation which is discussed later) which relates the peak of the Planck curves to wavelength.

A real body however emits only a fraction of what a black body emits at any given temperature. The spectral radiance of a real body is given by a modified form of the Planck radiation law:

$$N_\lambda = \epsilon_\lambda C_1 \lambda^{-5} (\exp(C_2/\lambda T) - 1)^{-1} \quad (2)$$

The term ϵ_λ is called the emissivity and is defined as the ratio of what a real body emits at a given temperature to what a black body emits at that temperature (i.e. $\epsilon_\lambda \leq 1$). In general emissivities of real bodies are functions of wavelength, temperature and surface condition. For fast measurements, though, the emissivity can be considered to be a function only of wavelength. The

Figure 1 - Spectral radiance curves at different temperatures, as predicted by the Planck radiation law.

emissivity of these bodies can easily vary by 10% over fairly small wavelength ranges. Therefore, any pyrometer that does not take emissivity changes into account can produce significant errors. Additionally because emissivity is rarely known for a given set of circumstances it must be either measured or calculated separately if an accurate temperature determination is to be made.

STATE OF THE ART

The most sophisticated technique of noncontact temperature measurement available today is Ratio or two-color pyrometry [1]. This method uses an approximation of the Planck relation called the Wien radiation relation:

$$N_{\lambda} = \epsilon_{\lambda} C_1 \lambda^{-5} \exp(-C_2/\lambda T) \quad (3)$$

The Wien relation can be solved for temperatures at two different wavelengths to give:

$$T = C_2 \frac{(\lambda_2 - \lambda_1)}{\lambda_1 \lambda_2 \{5 \ln(\lambda_2/\lambda_1) - \ln(N_1/N_2) + \ln(\epsilon_1/\epsilon_2)\}} \quad (4)$$

If the wavelengths λ_1 and λ_2 are chosen such that gray body behavior can be assumed (i.e. $\epsilon_1 = \epsilon_2$) then the emissivity term drops out and the temperature measurement is straight-forward. The assumption of gray body behavior becomes more valid as $\Delta\lambda = (\lambda_1 - \lambda_2) \rightarrow 0$ but as $\Delta\lambda \rightarrow 0$ any errors in the radiance measurements become more significant. Increasing the separation of the wavelengths reduces the effects of radiance measurement errors but the gray body assumption becomes less valid.

References [1-3] provide a thorough analysis of the errors associated with this technique.

MULTIWAVELENGTH THEORY

To increase the accuracy of the temperature measurement farther, the emissivity must be modeled better. This can be achieved by measuring the spectral radiance at a larger (>2) number of wavelengths. The term multiwavelength pyrometry refers to a set of techniques that measure radiance at n different wavelengths and then fit this data to a model that has m undetermined parameters ($m < n$), to calculate both the temperature and the emissivity simultaneously. The fitting model consists of the modified Planck function (Eq. 2) with a relation containing the $m-1$ undetermined parameters for the emissivity. The primary strength of multiwavelength pyrometry is that it makes only one assumption about the emissivity, namely, that the spectral emissivity has a smooth first derivative.

There are three solution techniques that fall under the heading of multiwavelength pyrometry, namely, interpolation based, linear least squares (LLS) and nonlinear least squares. Due to the limited nature of this communication we shall limit our discussion to the LLS technique. For a more detailed account of all these techniques see [2,3].

LLS imposes one further limitation on the emissivity model function i.e. that it must be linear in the undetermined parameters. Additionally we are restricted to using Wiens approximation (eq. 3) rather than Plancks law.

The LLS method works by minimizing the error between a model function and the measured data. The model function contains m undetermined parameters which are assumed to have achieved their true value at this minimum. If the model function is linear with respect to the undetermined parameters, the LLS method will yield an analytical solution (it cannot be used if the model function is nonlinear in these parameters). In matrix notation we describe the technique as the problem of minimizing ρ , when

$$\rho = \|AX - B\|. \quad (6)$$

Here B is an n -dimensional vector containing the measured data, X is an m dimensional vector containing the undetermined parameters and A is an $n \times m$ coefficient matrix. The symbol $\|C\|$ refers to the square root of the sum of the squares of the terms of C and is called the 2-norm of C .

Khan [3] has shown that the relative error in the parameter estimation is limited by the following relation

$$\text{Relative Error} < K * (\text{relative random noise in the data}) \quad (7)$$

This equation says that *the error or the uncertainty in the calculation of the undetermined parameters is always less than some multiple of the perturbation of the radiance data due to the measuring instrument*. The perturbations of the radiance data can be either systematic or random in nature. The systematic variations can be caused by systematic nonlinearities in the measuring radiometer and/or by an incorrect calibration of the radiometer. These variations are not too troublesome if they are not too large, as would be the case for any reasonably designed radiometer. The random variations introduced into the radiance data due to random variations or electrical noise in the radiometer, however, are more troublesome. These appear as an uncertainty in the estimated values of the parameters after being amplified by some factor 'K', i.e. a 1% random variation in the radiance data would appear as a K% uncertainty (error) in the parameter solution.

K is a function of the wavelength range and the specific function chosen to model the emissivity. For example K is approximately equal to 7 for a constant emissivity and about 130 for a linear exponential emissivity.

COMPUTER SIMULATIONS

A computer model was developed to test the ability of the aforementioned techniques to predict temperatures, emissivities and the associated errors. The following flow chart describes the simulation procedure.

Figure 2 - Flowchart describing the simulation procedure

Figure 3 depicts some of the emissivity data (curve fit to cubic polynomials) used for these simulations. The data were extracted from the literature [4,5]. Figure 4 presents the results of some of the simulations for Iron, Platinum and Molybdenum at 1600 K and for two noise levels. The figure shows that the theory is indeed capable of predicting the error in the parameter estimation. Although at the higher noise levels the theoretical predictions are very conservative.

A large number of these simulations were performed for different materials and at various temperatures and noise levels.

EXPERIMENTAL VERIFICATION

The instrument constructed to test the theory presented here, (known as the MITTMA) consists of a personal computer and a commercial spectrograph that is portable and is about the size and weight of a video camera. This system was configured to measure radiances at 135 wavelengths simultaneously. These radiance data were calibrated for detector and optics variations using a Black Body Radiance source and then passed to the temperature calculation routines.

The minimum temperature accurately (within 1%) measurable using the MITTMA in its present configuration is around 1200 K. This lower limit is imposed by the detector sensitivity. At present the system uses silicon photodiodes which are useful in the .5 to 1.1 micron wavelength range. The low temperature limit could be easily extended by going to a detector which is sensitive further out into the infrared spectrum, such as InSb.

Table 1 lists the results of some of the experiments performed using the MITTMA. As can be seen from the data in table 1, these techniques can measure temperatures with an accuracy similar to that of thermocouples if a sufficiently noise free signal is available.

Figure 3 - Emissivity data from the literature and the approximating polynomials.

Figure 4 - Simulation results for Iron, Platinum and Molybdenum at 1600 K. This figure shows the effect of an increase in the measurement noise (from 0.1% to 0.5% rms) on the uncertainty in the parameter estimation.

Source	Thermocouple Temperature (K)	MITTMA Temperature (K)	% Difference
Tungsten Strip	2625	2617	0.3
Black Body with Filter A	1234	1241	0.6
Black Body with Filter B	1233	1251	1.5
Platinum Strip	1255	1251	0.32
Platinum Strip	1121	1155	3.0
Platinum Strip	913	970	6.24

Table 1. Results of the experiments on different sources.

In order to simulate the effects of a changing emissivity at a constant temperature the temperature of a black body, viewed through different filters, was measured. The results of two of these experiments are presented in table 1. The two filters used are identified here as A and B and their transmissivities are shown in figure 5. This filter combination can be thought of as simulating the effects of oxidation of a surface, where the material goes from having a shiny, low emissivity surface (filter B) to a dark high emissivity surface (filter A). It should be pointed out here that filter B gives worse results because the shape of its transmissivity curve somewhat resembles that of the Planck curve thereby causing the curve fitting techniques to become confused between the effects of temperature and emissivity. This phenomenon is referred to as 'correlation' and is discussed in detail by Khan [3]. Nonetheless it can be seen from these results that accuracies of better than one percent are achievable using these techniques.

Figure 6 presents a comparison between the theoretical and experimental error in the temperature estimation for the platinum strip source. This figure plots the percent difference between the MITTMA predicted temperature and the thermocouple temperature for a number of measurements of this source at a constant temperature versus the measurement number. This figure also plots the theoretically predicted error (eq. 7) versus the measurement number. Again

Figure 5 - Transmissivities of the filters used to simulate the effects of oxidation of a surface.

Figure 6 - Comparison of the experimental and theoretically predicted errors in the estimation of temperatures for the platinum strip source.

we find that the MITTMA temperature has an average difference of only .8 percent from the thermocouple temperature and, just as importantly, the error predicted by equation 7 is also about .7 percent. We therefore have a reliable method of estimating the accuracy of our temperature calculations.

The multiwavelength techniques presented here and in [3] have the additional advantage that they can be used to calculate the emissivity of the surface as well as the temperature from the same set of measurements. Figure 7 presents the results of four of these calculations for the platinum data of figure 6. Specifically these emissivity vs. wavelength curves correspond to measurements number 4, 5, 6 and 8 with errors of +4, -1, -8 and -16 K respectively. Due to the nature of these techniques it can be shown [3] that the relative error in the emissivity estimation is much greater than the relative error in temperature estimation for a given set of data. Figure 8 bears out this observation in that the variation from measurement to measurement is high as fifty percent and it is extremely unlikely that the emissivity actually changed by fifty percent during these measurements. Nonetheless if the techniques really are performing as well as is claimed here then one would expect that the real emissivity of platinum would lie somewhere between the two emissivity curves corresponding to the -1 and +4 K errors. An examination of the published emissivity data [5] for clean platinum strip shows that this is indeed true to within the accuracy of that data.

CONCLUSIONS

The theory developed here has been shown to be capable of calculating true temperatures of any material from radiance measurements at a number of different wavelengths. This theory has also been shown to be capable of predicting the uncertainty in these calculated temperatures.

An additional advantage of these techniques is that they can estimate the emissivity of the target simultaneously with the temperature. This aspect can prove to be very important when a fast method of generating reflectivity vs. wavelength or emissivity vs. wavelength data is required. It is presently both difficult and time consuming to generate such data.

Experiments performed on various materials over a range of temperatures and experimental conditions have been used to verify the accuracy of this theory.

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Figure 7 - Calculated spectral emissivities for platinum. The four curves correspond to four separate measurements and therefore to four distinct temperature errors. The true emissivity of platinum would lie between the curves corresponding to the -1 and +4 K errors.

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ABSTRACT

A Workshop was held January 17 through 19, 1989 in Pasadena, California to review the state of the art in noncontact temperature measurement (NCTM) technology and to identify the NCTM requirements of the National Aeronautics and Space Administration (NASA) microgravity materials processing community. The workshop scope included technical presentations and discussions which ranged from research on advanced concepts for temperature measurement to laboratory research and development regarding measurement principles and state-of-the-art engineering practices for NCTM methodology in commercial and industrial applications.

Technical presentations were made concerning (1) NCTM needs as perceived by several NASA centers, (2) recent ground-based NCTM research and development of industry, NASA, academia and selected national laboratories, (3) work-in-progress communication and, (4) technical issues of the implementation of temperature measurement in the space environment to facilitate future U.S. materials science investigations.

The workshop was attended by approximately eighty scientists and engineers from diverse organizations including academia, industry, NASA and selected national laboratories. These proceedings contain the manuscripts and abstracts which were submitted by the authors of the invited papers, together with the summaries of findings and recommendations of the session chairs. The recommendations address identified needs to establish and extend thermophysical and thermoradiative materials properties data in support of fundamental temperature measurement, to identify and develop a series of objective temperature measurement instrument evaluation criteria and standards (particularly for thermal-imaging instruments), to continue vigorous research concerning applicability and limits of error for various radiation thermometry methodologies, and to continue the development of new NCTM technologies which will facilitate future quantitative materials science investigations.

FOREWORD

The space environment permits scientists from around the world access to a completely new laboratory unfettered by the constraints of our earthbound habitat. Unique to this new laboratory environment is microgravity, where very low accelerations can be achieved and maintained for significant durations; this permits detailed study of the behavior of materials in a variety of temperature regimes. One facility under development for this new laboratory is a containerless processing facility. Here, samples can be positioned in free space without the externally applied reaction forces which would be required to counteract the gravitational acceleration that would be encountered on earth.

The potential for science investigations in both microgravity and containerless science are exciting and broad because of the variety of materials and temperature ranges which can be explored. However, the conduct of scientific investigations in this new laboratory requires advanced capabilities and instruments that allow noncontact sample and process characterization. A very important area for this characterization is noncontact temperature measurement (NCTM), for which this workshop was convened in January 1989 in Pasadena, California.

The need for noncontact temperature measurement was identified at the April-May 1987 National Aeronautics and Space Administration (NASA) workshop held in Washington, D.C., and chaired by Dr. Mark C. Lee. The proceedings are documented as NASA Conference Publication 2503, dated 1988, and available from NASA's Scientific and Technical Information Division. An excerpt from the foreword of that document identifies NCTM and several other areas of advanced technology development:

"Noncontact Temperature Measurement Instrument has been identified as one of the eight advanced technology development (ATD) areas to support the Microgravity Science and Applications Division's effort in developing the six space Station Flight Experiment Facilities. The other seven ATDs are high resolution/high rate video technology, microgravity fluid diagnostics, laser light scattering instrument, vibration isolation technology, high temperature furnace technology, high temperature material [sic] technology, and interface measurement. Those ATD areas are defined as generic areas of technology advancement that will enhance the scientific integrity and quality of flight experiments. These technologies shall not be in the critical path of ongoing programs or near term facility development programs."

Further clarification of particular scientific needs is required to effectively manage the advanced technology that is oriented toward the enhancement and enablement of space-science experiments. The scope of the reported work includes approaches to instrumentation for the measurement of temperature over rather broad ranges and a general consideration of materials and processes that require temperature measurement. The materials include both condensed and uncondensed matter; much of the scientifically interesting phenomenology involves changes of state and nonequilibrium processes, including solidification and the processes of crystallization.

Significant progress has been made in investigating capabilities of advanced techniques for temperature measurement. However, further work is needed to establish the requirements for NCTM in support of future, and undesignated, science experiments. As this requirements definition proceeds, the adequacy of developing NCTM capabilities can be evaluated, and further technical advancements which are needed can be identified. Because of the ongoing nature of this work, it is anticipated that a follow-up workshop will be held near January 1991 to extend our understanding of the fundamental technological barriers of NCTM for advanced science experiments, and to revisit the technological capabilities in NCTM that are under continuing development.

SUMMARY OF PROCEEDINGS CONTENTS

Robert R. Hale

This document is organized into sections that closely parallel the framework of the technical workshop itself.

Section 1, NASA NCTM Needs by Center, contains the manuscripts prepared by each Center that describe the perceived needs for noncontact temperature measurement (NCTM) in support of science thrusts and microgravity science laboratory facilities at the various centers. The contributing National Aeronautics and Space Administration (NASA) Centers are the Jet Propulsion Laboratory (JPL), NASA Langley Research Center (LaRC), NASA Lewis Research Center (LeRC), and NASA Marshall Space Flight Center (MSFC). The breadth of the temperature measurement needs is well described in the presentations by G. Santoro of Lewis and E. Trinh of JPL.

Session 1 emphasized the state of the hardware for commercial and industrial thermal measurement and imaging systems. Of these papers, that by Chairman H. Kaplan provides a definitive organization and description of various types of thermal measurement instruments, their use in industrial and commercial materials and process measurement, and a list of manufacturers and suppliers.

The other papers dealing with thermal imagers described both in-process and planned development work in infrared imaging systems for use in space experimentation.

Section 2 contains technical discussions regarding capabilities in NCTM ranging from advanced concepts and innovative approaches to developmental temperature-measurement instruments. In the former area, important physical principles involving photoacoustic and thermal-wave phenomena and magnetic-resonance imaging are introduced. These topics are in keeping with the initial intent of the advanced technology development, which is to explore the characterization and measurement that enable advanced, and as yet undesignated, microgravity materials science. In addition to this long-term potential, instruments under development provide a nearer-term capability that, with adequate further development, may lead to successful flight instrumentation in a few years. Also, there are presently available industrial and commercial thermal imagers that have the potential for at least relative thermal measurements in ground-based and flight experiments. These instruments provide large amounts of imaging information of high value for defense and industrial uses. The successful adaptation of such thermal imagers to quantitative scientific temperature measurement will require a significant technical effort.

Other papers in this section describe the calculation of true temperatures from radiance measurements made at a number of different wavelengths (Kahn), the use of ellipsometry to determine optical constants and temperature (Krishnan), an instrument using multiwavelength imaging pyrometry to measure small moving samples (Frish), and innovative uses of thermal imaging anomalies for the control of crystal growth (Wargo).

The original plan for Section 2 was to investigate, in depth, the technical issues in the dynamic response of thermal measurement and its relationship to thermal control. This was considered important for two reasons. The first is the rapidity with which some microgravity experiments occur. An example is recalescence in which a spontaneous and very rapid temperature increase is seen subsequent to subcooling a liquid. The second is the detailed knowledge required of the dynamic interaction of the measured signal with the time response of the control element. This knowledge will be needed for the expected future use of the temperature measurement signal as an element for control within the experiment itself. Because much temperature measurement work involves temperatures that are unchanging or changing slowly, special emphasis on this topic with regard to microgravity science is indicated. Considering that much of the actual technical work involving dynamic response is inextricably linked to thermal and thermal radiative properties of materials, it was felt necessary to combine the technical expertise and experience of the Session 3 chairs with those of Session 2.

Section 3 is an update regarding the thermal requirements for materials science investigations. These requirements will be used to help define more specifically the thermal measurement barriers that limit the characterization of fundamental behavior in advanced materials science.

In this section is previously undocumented research in materials science, including polymeric materials investigations (Coulter) and overview comments on thermal issues relating to high T_c materials – an emerging materials and process technology (Bishop).

Section 3 also discusses significant differences in the time regimes, temperature ranges, temperature change rates, and spatial temperature gradients, which are of importance in understanding and controlling an experiment or process.

Because of the interrelationship and time rates of change of radiant intensity as a function of wavelength, dynamic response also is associated with multicolor pyrometry. Therefore, Session 4 was also combined with 2 and 3, making one large concurrent splinter session. (The paper by C. Y. Ho describing the numerical database (CINDAS) at Purdue University was presented in plenary session prior to segregation into the splinter work groups.) Section 4 contains the technical papers presented within the splinter work sessions.

Section 5 presents the summary findings of each of the session chairs. Many were unable to present consensus findings because of time limitations and the combination of the three topical sessions into one large splinter group.

Section 6 contains Appendixes. Appendix A is a list of attendees to the workshop; Appendix B is a list of NCTM Requirements as extracted from NASA Conference Publication 2503 in 1988 (Mark C. Lee, Editor); Appendix C consists of letters of invitation and welcome, the final program, and selected abstracts from the workshop.