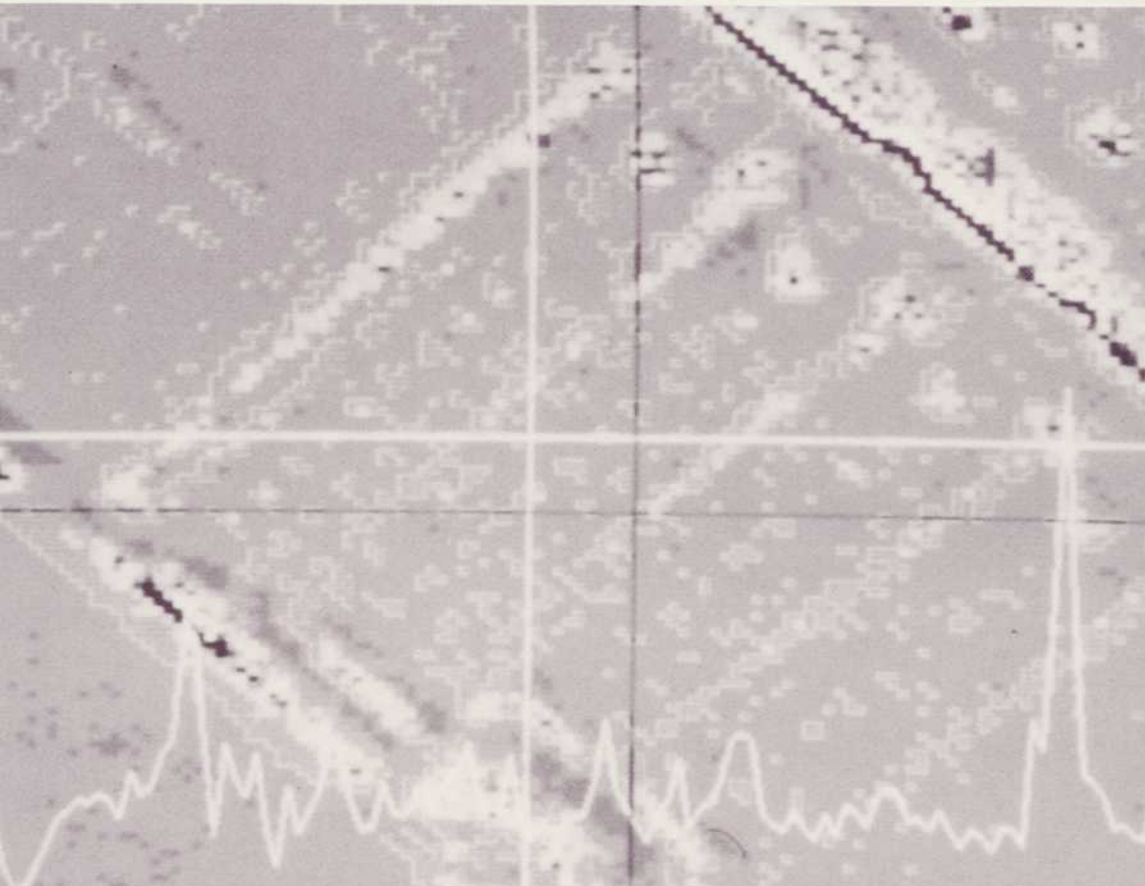
Applications of RADIATION THERMOMETRY



RICHMOND/DEWITT, editors

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APPLICATIONS OF RADIATION THERMOMETRY

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Foreword

This publication, *Applications of Radiation Thermometry*, contains papers presented at the Symposium on Applications of Radiation Thermometry, which was held at the National Bureau of Standards, Gaithersburg, Maryland on 8 May 1984. The symposium was sponsored by ASTM Committee E-20 on Temperature Measurement in cooperation with the National Bureau of Standards. D. P. DeWitt, Purdue University, presided as symposium chairman. He and J. C. Richmond, Bureau of Standards, are coeditors of this publication.

Related ASTM Publications

Thermoelectricity: Theory, Thermometry, Tool, STP 852 (1985), 04-852000-40

Manual on the Use of Thermocouples in Temperature Measurements, STP 470B (1981), 04-470020-40

Evolution of the International Practical Temperature Scale of 1968, STP 565 (1974), 04-565000-40

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

ASTM Committee on Publications

ASTM Editorial Staff

Acknowledgments

Considerable effort on the part of many individuals is required to produce a successful symposium and a special technical publication. In addition to acknowledging the primary contributions by the authors, the editors wish to thank the numerous reviewers who provided thoughtful, constructive criticism that resulted in papers of high quality. Special thanks go to Kenneth G. Kreider, Division of Chemical Engineering Metrology, National Bureau of Standards (NBS), for serving as the local arrangements chairman for the symposium, held in the superb facilities of the NBS. The program committee, consisting of G. Ray Peacock, Chairman of the ASTM E20.02 Subcommittee on Radiation Thermometry, Land Instruments, Arthur E. Goldberg, Ircon, and William R. Barron, Williamson Corp., deserve considerable credit for their organizational efforts and stimulation of paper contributions. Robert L. Shepard, Oak Ridge National Laboratory, chairman of ASTM Committee E20 on Temperature Measurement, deserves thanks for encouraging us to undertake the effort to hold a symposium on this growing field of temperature measurement.

It is appropriate to note that this publication is of special significance to one of the editors. Joseph C. Richmond is a charter member of ASTM Committee E20, formed in 1962, and since that time he has made extensive contributions to the fields of radiative properties and radiometric measurements. After 46 years of service to the National Bureau of Standards, with the last five on a consulting basis, his most recent contribution is that of editing this first special technical publication on the applications of radiation thermometry. The entire subcommittee takes this occasion to acknowledge Joseph Richmond's significant role over the past 23 years and with regard to this particular publication.

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Recent Developments

Overview

Methods of temperature measurement using radiation thermometers, also referred to as optical or infrared pyrometers, are becoming more attractive for industrial applications. In addition to the noncontact and remote sensing advantages, the methods can be realized by a wide selection of thermometer types. With the growing use of computers for control purposes and the increased opportunity for improving process productivity and product quality, it has become essential to understand better the performance of radiation thermometers in the industrial environments where they are applied.

A radiation thermometer (RT) is a radiometer calibrated to indicate correctly the temperature of a blackbody. The radiometer, whether it be of the spot-type or a line or area scanner, senses the radiant flux from the target and provides a signal that, through a calibration algorithm, provides a measure of the target temperature. The most demanding situation is that of a nonblack target in the presence of hotter surroundings with a gaseous atmosphere that absorbs, scatters, and/or emits radiant flux. The procedure for inferring the target temperature from the RT-indicated temperature is referred to as the *measurement problem* and for the described situation can be extremely difficult to accomplish with high accuracy.

Fortunately, many industrial applications are not so complicated, and the temperature measurement using the proper RT is simply a point-and-read procedure. For targets that are freely radiating (cooler surroundings) for which there is an estimate for the spectral emissivity, the RT provides reliable measurements. For targets that approximate gray bodies with constant spectral emissivity, a ratio RT (two-color pyrometer) operating at properly selected spectral band passes provides a reliable method for measuring temperature without knowledge of the target emissivity. There are numerous important industrial applications where these conditions are satisfied, and RTs provide cost-effective solutions for temperature measurement and control.

The successful practitioner knows how to formulate the measurement problem and recognizes when nonblack or semitransparent target effects, reflected irradiance from surroundings, and participating atmospheres are important for the application. Prerequisites for addressing the problem are a knowledge of the physics of thermal radiation and of the design/construction/calibration of RTs. Also helpful is a background on experiences of other users who have successfully solved their application problems.

The objectives of the Symposium on Applications of Radiation Thermometry were: to inform the technical community about recent advances and new technology in this growing field of temperature measurement, to provide a forum for exchange between new and experienced users, and to establish a more formalized literature base on the theory and practice of radiation thermometry. These objectives are consistent with the broad responsibilities of the two sponsoring organizations, the National Bureau of Standards (NBS) and the American Society for Testing and Materials (ASTM), Subcommittee E20.02 on Radiation Thermometry.

Organization of the Symposium

The symposium was presented in four sessions. The first session dealt with the principles of measurement and methods for calibration. The second session presented industrial applications using a case history approach to provide an overview on situations where RTs have been successfully employed. The next session concerned research and development in the field, and two topics were presented as especially relevant to the objectives of the symposium. Finally, a panel composed of practitioners, manufacturers, and researchers addressed current problems in the field, including test and calibration methods and user education.

Principles of Measurement and Calibration

The purpose of this session of the symposium was to present overviews on the principles of measurement by radiation methods and of calibration methods from the perspective of a national laboratory and an industrial organization.

The first paper, "Radiation Thermometry—The Measurement Problem" by Gene D. Nutter, considers RT problems in three parts: the radiator (target), the environment between the radiator and the RT, and the characteristics of the RT itself. The treatment on radiators begins with the classical introduction of the directional and spectral radiance from blackbodies and real surfaces. The optical properties and spectral emissivity of real metallic and dielectric materials are described; the understanding of materials behavior is a necessary prerequisite for rational application. The effects of the environment are introduced, especially those due to irradiation originating from the hotter surroundings reflected from the target and due to atmospheric effects. The manner in which these effects can be accounted for or minimized is described. The principal characteristics of narrow-band RTs are introduced, including treatment of photodetector types and infrared material properties. The measurement equation relating signal output to target parameters and RT characteristics is explained. This equation provides the basis for inferring true temperature from the RT-indicated temperature. The paper provides a useful review of the physics of thermal radiation and an introduction to the field of radiometry.

In the paper "Methods of Calibration at a National Laboratory," Richard L. Anderson describes the radiation thermometry practices of the Metrology Research and Development Laboratory (MRDL) at the Oak Ridge National Laboratory (ORNL). MRDL is the intermediate link between the NBS and the individual researcher using an RT. The RT calibration requirements of this large research facility are of a wide variety with an emphasis generally on high accuracy. MRDL maintains primary NBS-calibrated, secondary laboratory and working standards in the form of tungsten strip lamps, standard optical pyrometers, and calibrated Type-S thermocouple wire. The procedures used for calibration of an optical pyrometer (effective wavelength of 0.65 μm) are described in detail. The effects due to sighting through windows, normally employed in high-temperature furnaces such as those used for materials processing studies, are discussed. MRDL also has responsibility to operate a maintenance information system for keeping systematic records of traceability and operating a computerized maintenance and calibration recall system.

The calibration requirements for industrial plants or operations may not be as varied and demanding as those for a national laboratory. Roy Barber writes about "Establishing a Calibration Laboratory for Industrial Radiation Thermometry" for those involved in the process of specifying a calibrating procedure for industrial-style RTs. Because of the wide array of instrumentation and calibration equipment, there are many acceptable alternatives to meet particular needs. The most difficult decision in planning may be a realistic definition of the needs in terms of range of temperature capability and accuracy. For example, it may be more important to have a very high repeatability of calibration (±1 K, for example) than to have a low total uncertainty of the measurement, say ±5 K. There may be an appreciable difference in the time and expense to perform these procedures. The newcomer to the field will especially appreciate Barber's introduction to primary and secondary sources and transfer sources, as well as his estimates of the accuracy routinely achievable by various approaches. Examples of equipment and the factors affecting their choice in performing calibrations over the range of temperature from 200 to 2600°C are presented. While proper equipment is essential for a good industrial laboratory, the two other major ingredients for success are competent engineering supervision and quality laboratory space with controlled air temperature and humidity. With clever English wit, Barber points out that once you pass through the phase of realizing that your uncertainties are not as good as you previously thought, you have a good laboratory.

Application Case Studies

RTs have been used successfully in many industrial situations. Some of these applications may be accomplished simply by using off-the-shelf instrumentation with minimum effort to properly infer target temperature from the indicated temperature. It is also possible that many application requirements are satisfied without knowing the target temperature; the indicated reading (process set point) may be sufficient for satisfactory product quality as determined by subsequent inspection or analysis. There are, of course, other applications where a considerable amount of engineering analysis is necessary to determine the RT specifications and a method for reliably inferring target temperature. Examples of such applications are indicated in subsequent papers.

This session began with an overview of radiation thermometry instrumentation entitled ''Radiation Thermometry—Status and Trends'' by William R. Barron and Arthur E. Goldberg. They explain that continued interest in productivity, product quality, and energy conservation make the noncontact features of RTs especially attractive. Particularily, the trend toward automation with process control has created more demand in the marketplace. A wide variety of instruments is currently marketed to meet diverse applications for process control, maintenance, energy auditing, and troubleshooting. Instrumentation types include sensor transmitters, portables, fixed-installation units, dual-wavelength devices, fiber-optic sensors, and sophisticated hybrid designs to meet special requirements. Recent years have seen a significant increase in the quality of instrumentation, improved ruggedness to operate in more hostile environments, and the growth of smart microprocessor-based designs. There are numerous allied technologies, such as lasers, fiber-optic communications, and microprocessors, that will continue to afford benefits to the instrument manufacturer. At present, the capability to manufacture quality electronic and optical designs is equal to the marketplace demand. The shortfall, if one exists, is the understanding of the measurement problem.

The first application study, ''A Review of Temperature Measurement in the Steel Reheat Furnace'' by A. P. Martocci and F. A. Mihalow, deals with the difficult measurement problem of viewing through combustion products at a surface (slab) being heated in a furnace. The influence of flames, irradiation from hotter furnace walls, combustion products absorption/scattering, steel oxidation/scale formation, and furnace gradients, to name a few, must be considered. The authors provide a description of furnace designs and how the slab proceeds through the preheat, heat, and soak zones. The solution is a dual-thermometer hybrid system; one RT senses spectral radiance from the target while the second thermometer (either an RT or thermocouple) provides a measure of the average furnace background temperature. The procedures used to verify proper performance are necessarily elaborate and involve the use of a telemetry package with thermocouples imbedded in the slab to provide temperature measurements as it proceeds through the furnace. The effort to solve this problem has spanned many years and has included extensive laboratory simulation experiments. This case study teaches that solutions to complicated problems require substantial investments of resources; necessarily, an enlightened management is required to recognize the benefit of sustained development work. Surely the dual-thermometer approach will have use in other situations. Also, it is recognized that an important aspect of the work is the need to evaluate RT performance under in-use conditions.

In the paper "Closed-Loop Temperature Control for High-Frequency Electric-Resistance Tube and Pipe Welding Mills," Humfrey N. Udall describes a case where the unique features of the ratio RT (dual-wavelength RT or two-color pyrometer) are well utilized. The tube or pipe, of widely varying diameters (to 1.3 m) and wall thicknesses (to 25 mm), moves at speeds from 7.5 to 150 m/min. Power to the high-frequency welding power supply is digitally controlled by the RT that sights on a region of the tube surface which may include only a portion of the hot-weld zone. Smoke and steam are usually in the sight path, and the emissivity of the tube surface is unknown and generally changes with the process. Experiences have shown that with adjustable set points high quality welds can be made over a significant range of tube-processing variables.

Temperature measurement is critical for the pressing of the faceplate of a TV tube, referred to as the panel. In his paper "Mold Temperature Measurement for Glass-Pressing Processes," Roger A. Holman explains that a variation of $\pm 1°C$ on the set point of the air-cooled metal mold can cause significant changes in the contour of the aspherical surface of the panel, so that close temperature control is required to produce panels within the dimensional tolerances. The narrow-band RT operates at a wavelength shown by extensive laboratory measurements of mold surface spectral emissivity to take advantage of minimum emissivity changes that occur as the mold goes from the preheated, clean state to a well-conditioned (after two days) state. Other factors important in the RT wavelength selection were the low temperature (450°C) and reflected ambient radiation. This case is an excellent example of the RT selection procedure as well as representative of a cost-effective application of RTs for control processes.

The paper "Radiation Thermometry for Semiconductor Crystal-Growing Furnaces" by Walter Helgeland reports another successful and important application of a ratio RT used for process control. In the process, a pool of molten silicon (20 to 45 kg) in a graphite cup is brought to a steady temperature slightly above its freezing point (1420°C), following which a small seed crystal is dipped into the pool and slowly raised, forming a single crystal rod. The shape of the formed crystal is dependent upon the pulling rate as well as temperature conditions in the furnace. The RT operates at 0.71 and 0.81 μm, conventional wavelengths for ratio instruments, and uses fiber-optics for convenience in viewing the furnace targets. With the process under satisfactory control, peak-to-peak fluctuations of 1.6°C and 2 to 10°C are observed for the graphite disk and silicon pool, respectively.

An application example with semitransparent targets is discussed by David A. Jacobson in his contribution entitled "Use of Radiation Thermometers for Temperature Control of Plastic and Paper Webs in Electric Infrared Ovens." From knowledge of the transmission spectra of polystyrene, the spectral bands (3.4 and 7 to 8 μm) where the film is highly absorbing (with but slight transmission) can be identified. The spectral distribution of radiation from an electric heater is dependent upon its type and its operating temperature: evacuated-tungsten lamps (2500 K), quartz panels (800 to 1225 K), and ceramic/metal-sheathed heaters (<800 K). The procedure for selecting the appropriate RT involves evaluating the effects of heater radiation reflected from or transmitted through the film into the field of view of the RT. The author demonstrates that it is not necessary to know the exact film temperature, but only to have an indicated temperature reading (set point) to achieve satisfactory film quality as determined by physical inspection of the end product.

In many applications, it is desirable to know the temperature distribution along a line or over an area of the target surface rather than just that of a spot target. Herbert Kaplan's paper, entitled "Thermal Imaging Systems for Measuring Temperature Distribution," begins with a brief historical review of scanning and imaging instruments and then presents case histories where such instruments have solved important problems: portable inspection of plant equipment (stacks, furnace insulations, etc.), thermal mapping of terrain, moisture penetration in flat industrial roofs, in-process weld control, nondestructive inspection techniques, and design verification of electronic assemblies. Recent developments suggest that new powerful thermal analysis tools will come from the interfacing of thermal imaging systems with computers or microprocessors. The reader not familiar with line or area scanner features and performance will find this paper a most useful overview.

Recent Development and Research Activities

Two different examples of research in the field of radiation thermometry are discussed. The first example concerns research on fiber-optic thermometry for use as an interpolating device for the thermodynamic scale (metrological application) and as a sensor for industrial temperature measurements. The second example is the development of hybrid methods that utilize auxiliary apparatus such as mirrors and sources for measuring surface temperatures without foreknowledge of the surface emissivity.

The fiber-optic thermometer (FOT) operates by emission of blackbody radiation from a thin-film metal cup on the end of a light pipe (present interest is on sapphire) which is immersed in the hot (gas) environment to be measured. The blackbody radiation is transmitted through the fiber optic to the photodetectors, using a ratio method (typically, 600 and 700 nm) to derive the cup temperature. Kenneth G. Kreider, in his paper "Fiber Optic Thermometry," briefly traces the history of its development for gas turbine applications (high temperature-high speed) and points out the advantages of this method for engineering applications. Two projects are in progress at NBS, both dealing with sapphire guides, with the objectives of (1) establishing the means for reducing the uncertainty in interpolating between two fixed points (aluminum and gold) on the thermodynamic scale and (2) providing the fundamental technology for using the FOT in harsh chemical process environments. Kreider reports on investigations to verify blackbody conditions with several tip (cup) geometries and platinum thin-film lengths. The ratio method is compared with reference thermocouple measurements and discussion is presented on sources of error. Recently the FOT has been commercially marketed, and we can soon look forward to learning about applications of this new method.

Participation by Japanese workers in the 1981 temperature symposium[1] made evident their high level of activity in many aspects of the field of radiation thermometry. Tohru Iuchi's paper, "Recent Advances and Research Activities in Japan," indicates that symposia and conferences are held regularly by Japanese technical societies and that cooperative research between national institutions and private companies is common. By comparison, our activities in the United States are more fragmented.

The major difficulties of stray radiation (reflected irradiances from hot sources) and target emissivity variation, inherent in nearly all RT applications, are especially troublesome in steel processing. As examples of the results of long-term research benefits, Iuchi describes six new methods developed at Nippon Steel for measuring temperatures in a variety of steel-making processes. The hybrid methods make use of cooled shields, auxiliary reference bodies, mirrors to cause multiple interreflections, and modulators. Three of these methods provide for simultaneous determinations of surface temperature and emissivity of the target. These hybrid methods are indeed more complicated than the simple RT, but it is necessary to recognize that if operating mill accuracies of 1% or better are required, such complicated methodology will be required. It is also important to recognize that development of these methods is a long-term activity requiring extensive commitment of effort. At this point, further advances in the mill technology will require serious research, bringing together the latest advances in the allied fields of instrumentation and microprocessors as well as an improved understanding of the effect of temperature on processes.

Panel Discussion and Summary

The technology of radiation thermometry is approaching maturity as manufacturers are providing a wide array of instruments including portable and fixed-installation types for nearly any spectral range with numerous features such as emissivity compensation, peak-and-hold, averaging, and the like. However, according to the panel under the moderatorship of G. R. Peacock, two concomitant problems are of concern: education of the user (and the designer, who is most likely an electro-optics specialist) on principles of radiation thermometry and reasoned engineering approaches to new applications.

Many users do not have sufficient background to select proper RTs for routine applications and fall short of appreciating the magnitude of the effort required to solve sophisticated application problems. Improper instrumentation specification and lack of success make more difficult the task of convincing engineering and plant management that radiation thermometry holds promise for cost-effective temperature measurement.

[1] "Temperature, Its Measurement and Control in Science and Industry," Vol. 5, Pts. 1 and 2, J. F. Schooley, Ed., American Institute of Physics, New York, NY, 1982.

At present, the education task is being borne by the instrument manufacturer; this seriously complicates and compromises their efforts to work with potential users on applications for which the requirements are not fully recognized or understood. The educational responsibility must be shared by the technical societies. In only a few instances, fortunately marked with high success, has industry accepted the role as collaborator with the instrument manufacturer to undertake significant research and development work. Too frequently application studies are initiated without the extent of commitment that is necessary to achieve success. Several of the case studies presented in the symposium provide examples of good engineering methodology.

ASTM has recognized the need for educational information, standards in the area of terminology, instrument test methods, and calibration practices. ASTM Subcommittee E20.02 Radiation Thermometry is in the process of writing manuals, including one addressing engineering-level applications. Also, the subcommittee has encouraged the preparation of a more scholarly treatment of the theory and practice of radiation thermometry which shortly will be published as an NBS monograph.[2]

Historically, primary steel manufacturing has been one of the principal users of RTs. The role of temperature measurement in basic processes for quality products was discussed at length by the panel. In achieving reliable measurements, two major problems need to be addressed: consistent use of standards by which RTs (and thermocouples) are calibrated and on-line verification of RT performance.

Industrial calibration equipment and in-plant services seem to be especially vulnerable to economy measures; management has a poor understanding of the role of an in-plant calibration laboratory. The problem is compounded then since few independent testing laboratories can provide instrument maintenance and calibration support on a regular basis.

The calibration and verification of RTs in their on-line condition is necessary in order to assure that correct temperatures are obtained. Some of the methods used in the steel industry for these purposes were discussed by the panel. Unless proper care is taken, the user may not be measuring the true target temperature but rather an indicated temperature that provides acceptable process control for specified conditions. Frequently, when operating conditions change—slightly different material composition/surface, change in process parameters (speed, temperature level, etc.)—the approach fails and the product is no longer meeting expected quality levels. Experience and practice suggest that it is important to know the true target temperature.

The future of radiation thermometry can be bright. Much of the instrumentation technology presently exists to address many new applications for process control, quality control, and manufacturing engineering. Improvements in the technology likely will keep pace as automation and intelligent manufacturing begin to impact

[2] *Theory and Practice of Radiation Thermometry*, D. P. DeWitt and G. D. Nutter, Eds., in press.

productivity. A better-informed and educated user will be necessary to take advantage of these exciting opportunities. Collaborative research activities, now modestly practiced in this country, need to be promoted in order to better understand details of the radiometric problems and their relation to the processes under study. Improvements in standardization and calibration practices must expand to provide better support of today's instrumentation and to prepare the way for more extensive use of radiation thermometry methods for industry.

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