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THE USE OF PYROMETRY IN THE STUDY OF FAST THERMAL PROCESSES INVOLVING INITIALLY SOLID SAMPLES

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The theoretical background relevant to the use of pyrometry in the study of fast processes involving rapid temperature changes initially solid samples is outlined. Pyrometers of various kinds are described briefly and their applications in the study of pyrotechnic reactions, schock-wave research, thermal imaging and the measurement of thermophysical properties are reviewed.

Introduction

The techniques of thermal analysis are normally applied to samples which are initially in a condensed phase, most commonly solids. The definition of thermal analysis applies strictly to samples subjected to controlled heating programmes. Methods have been developed for using thermal analysis to study heterogeneous catalytic reactions on solid surfaces [1], but application to homogeneous reactions between gases or in solution is not straightforward.

At least three major limitations affect the use of thermoanalytical techniques, irrespective of the state of the sample. These are : i) the maximum temperature ranges over which the sample can be studied with the materials and the sensors available; ii) the generally slow response times of the sensors available which limits the rate processes which are accessible to study; and iii) the problem of self-heating of the sample, and hence deviation from the controlled heating programme, when using relatively large masses of

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samples which undergo rapid strongly exothermic processes [2]. Such processes include solid-gas, solid-liquid and solid-solid redox reactions, e.g. the combustion of pyrotechnic systems [3–7], and the rapid intramolecular redox processes characteristic of the ignition and detonation of explosives.

This article reviews the applications of pyrometry (or radiation thermometry) in the study of relatively fast, high temperature processes developing from initially solid samples. The requirements imposed by the experimental conditions usually make it necessary that pyrometers be built specifically for the research efforts concerned. Some of these pyrometers are described in this review.

Basic theory

Any object at a temperature, *T*, above zero kelvin radiates energy in all directions. For a perfect blackbody (i.e. a body with a surface which absorbs all radiation, at any wavelength and all temperatures, without reflecting any and is thus also a perfect radiator) the intensity and the spectrum of the blackbody radiation at a given temperature are governed by the Planck equation. If $\rho\lambda$ is the radiant energy density (intensity) at a given wavelength, λ, then the energy density, $\mathrm{d}U$, in the range λ to $\lambda + \mathrm{d}\lambda$ is given by

$$\mathrm{d}U = \rho\lambda\, \mathrm{d}\lambda = (C_1/\lambda^5)\left\{\exp(C_2/\lambda T) - 1\right\}^{-1} \mathrm{d}\lambda$$

where C_1 is equal to $8\pi hc$ ($= 4.992\ 49 \cdot 10^{-24}\ \mathrm{J \cdot m \cdot s^{-2}}$) and C_2 is equal to hc/k ($= 1.438\ 77 \cdot 10^{-2}\ \mathrm{m \cdot K}$), and h is the Planck constant.

A plot of the intensity against wavelength at various blackbody temperatures is shown in Fig. 1.

The total energy density at wavelengths from $\lambda = 0$, to $\lambda = \infty$ is

$$U = \int_0^\infty \rho\, \mathrm{d}\lambda = aT^4$$

where $a = 4\sigma/c$, and c is the speed of light. σ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$). This relationship is commonly referred to as Stefan's Law and may also be written as

$$M = \sigma T^4$$

where M is the excitance or the power emitted per unit area.

The wavelength of maximum radiation intensity, λ_{max} varies with temperature and may be derived from the Planck distribution by determining the wavelength for which $dU/d\lambda = 0$. The result, known as Wein's displacement law, is

$$T\lambda_{max} = 2.878\cdot 10^{-3}\,\mathrm{K\cdot m}$$

and is plotted as a dashed line in Fig. 1. The higher the temperature of the blackbody, the shorter the wavelength at which maximum intensity occurs.

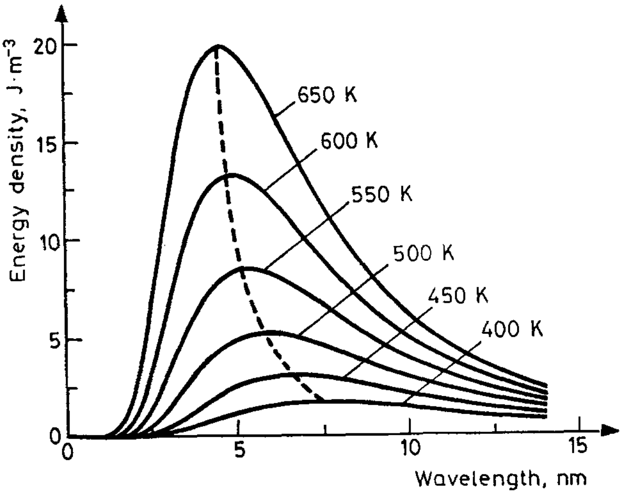

Fig. 1 A plot of energy density against wavelength at various blackbody temperatures

Blackbody radiation characteristics may be expressed [8] in terms of hemispherical measurements which consider the loss of radiation, in all directions, from a surface. The radiation-loss from the surface is obtained by integrating the radiant energy density over the solid angle of a hemisphere of unit radius. So, the hemispherical total energy density is

$$W = \int_0^{\pi} \rho_\theta d\omega$$

where ρ_θ is the energy density at the angle θ and $d\omega$ is the solid angle normal to the surface. The result of the integration yields

$$W = \pi\rho$$

Planck's equation, in hemispherical terms, is thus

$$W_\lambda = \pi\,(C_1/\lambda^5)\left\{\exp(C_2/\lambda T) - 1\right\}^{-1}$$

Much of the literature which describes radiation pyrometry is written in terms of hemispherical emissions [8].

For a non-blackbody (actual) surface

$$M = \varepsilon\sigma T^4$$

where ε is the emittance of the surface and may range from zero to one.

There is some confusion [8] between the terms 'emittance' and 'emissivity'. Emissivity is an idealized concept for a perfect surface, while emittance is a similar property of real surface.

The emittance of any given surface, varies with the wavelength of the radiation emitted. When the source-body has a constant emittance over a short range of wavelength, the body is known as a 'grey body'. The emittance may be measured at a single wavelength, over a wavelength range, or over all wavelengths. Emittances must be known to be able to convert radiant heat transfer measurements to temperatures.

The response of a pyrometer to incident radiation may be expressed [9] as

$$P(\lambda, T) = W(\lambda, T)\,r(\lambda)\,\mathrm{d}\lambda$$

where $W(\lambda, T)$ describes the spectral radiance characteristics of the source, and is given by Planck's distribution. The function $r(\lambda)$ describes the spectral response characteristics of the instrument

$$r(\lambda) = A\omega RR_\mathrm{d}(\lambda)\,\varepsilon(\lambda, T)\,\zeta(\lambda)\,\Delta\lambda$$

where A is the target area, ω is the solid angle of radiant flux incident on the field-defining aperture, R is a contribution by various electronic gain factors, R_d is the responsitivity of the detector, ε is the emittance of the target, $\zeta(\lambda)$ is the attenuation by the optical elements, and $\Delta\lambda$ is the spectral bandwith of the detector. $r(\lambda)$ therefore depends on both the specific components of the pyrometer and on the physical characteristics of the surface being measured. It is thus too complicated to be calculated from first principles. Some of the difficulties in evaluating these equations have been overcome, by introducing the concept of a grey body (see above).

Types of pyrometers

There are basically three types of pyrometers: wideband, narrowband and ratio (or two-colour) pyrometers. Wideband pyrometers respond to a wide range of wavelengths and usually have thermistor bolometer or thermopile-type detectors. Narrowband pyrometers have filters which allow only a narrow range of wavelengths to pass through to a detector. This detector, usually a photodetector, has a maximum sensitivity in the wavelength band transparent to the filters.

In ratio (two-colour) pyrometry, filters allow two narrow bands of wavelengths to pass through to two independent photodetectors. The principle of the method [10] is that, using the Wien approximation for the Planck equation, the ratio, Q, of the spectral radiances at two wavelengths λ_1 and λ_2 will be

$$Q = (\varepsilon_1/\varepsilon_2)(\lambda_1/\lambda_2)^5 \exp[(C_2/T)((1/\lambda_1) - (1/\lambda_2))]$$

so that if the ratio $R = (\varepsilon_1/\varepsilon_2)$ is known, T can be calculated. Other quantities which are dependent on wavelength but not on the source temperature, such as the transmittance of the intervening atmosphere and the spectral sensitivity of the detectors, may contribute to an effective value of R. The sensitivity of the method increases as the separation of wavelengths increases, but so does the uncertainty in the knowledge of R [11].

Detectors

Radiation detectors which operate over the ultraviolet, visible or infrared regions of the spectrum are called photodetectors, and fall into two main classes [12]: thermal detectors and photon detectors. Photon detectors may be further classified as photoemissive devices or solid state sensors. The quantum efficiency of a photon detector is the ratio of the number of electron events per second occurring as a result of irradiation, to the number of photons per second received by the detector. In high performance detectors values of around 0.7 may be achieved.

In pyrometry, infrared detectors are the most important since the bulk of the energy emitted by an object from ambient temperature to several thousand kelvin lies in the near infrared region (Fig. 1).

Thermal detectors include [12] thermopiles (based on the Seebeck effect) and bolometers (resistors with small heat capacities and large temperature coefficients of resistance). The original devices have often been superseded by semiconductor and/or superconductor devices and rapid developments continue. Detectors of pyroelectric materials may be used for following changes in temperature.

Photoemissive detectors [12] produce electrons on exposure to radiation and many different materials have been used successfully over different spectral regions. Amplification of the signal is achieved through use of photomultipliers.

In solid state photon detectors, radiation does not cause emission of electrons, but the excited species formed remain within the detector material and usually alter the electrical properties of the material quantitatively so that electrical measurements can be used as measures of the radiation received.

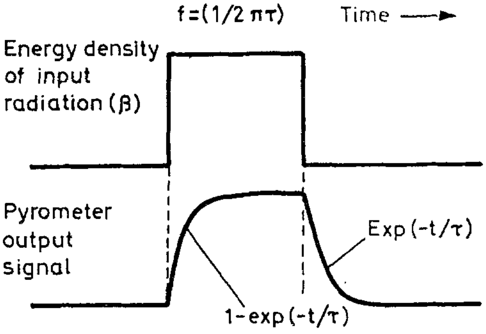

Fig. 2 Response of a pyrometer to a square-wave input, defining the detector response time

The response time, τ, of a detector is defined as the time taken to rise to $\{1-\exp(-t/\tau\}$ of the peak value or to decay to $\exp-(t/\tau)$ of the peak value, as shown in Fig. 2, when the detector is exposed to pulsed radiation with square wave characteristics [12, 13].

Examples of pyrometer systems

The need to measure the thermophysical properties of materials (e. g. thermal expansion and thermal conductivity) at high temperatures achieved by rapid heating rates, has resulted in the development of pyrometers capable of millisecond and, later, microsecond time resolution [14, 15].

A high speed optical pyrometer capable of 1200 measurements per second was described by Foley [14] in 1970. The pyrometer consisted of an optical system (providing for a constant aperture and target area), a narrow band optical filter (0.65 μm) and an electron multiplier photocell, which was illuminated alternately by light from a reference source and from the experimental source. A rotating shutter and attenuator disk limited each exposure of the detector to the source-body to approximately 0.2 ms. The data collected were processed in 'real time' and this was claimed to improve the precision of the readings.

Beckwith and Crane designed a two-wavelength pyrometer specifically for the direct measurement of the temperature of the surfaces of metals upon irradiation by laser [16]. The radiation from the source-body was transmitted through filters (0.2 and 2.5 μm) which were centered on a chopper wheel. The sensor consisted of a single photoconductive cell with an inbuilt refrigeration cell. The detector signal was amplified by stepwise gain stages which incorporated electronically variable attenuators to prevent overload of the amplifier when very hot surfaces were measured. A two-phase analogue switch separated the two signals S_1 and S_2 (corresponding to λ_1 and λ_2 respectively). S_2 was held constant by an automatic-gain control loop. The signals were then filtered electronically and converted into a ratio by a standard analogue divider. On testing the instrument, it was shown [16] that heating rates of $3 \cdot 10^4$ deg$\cdot$s^{-1} were measurable, and that the instrument was not susceptible to 'instrumental hangover' as a result of previously measured high signal levels.

The usual chopping and demodulation may be dispensed with if it is assumed that the amplifier and detector drift are negligible for the duration of the experiment [17]. Righini used two computer-actuated rotary solenoids to expose the detector to the target and reference signals. The data acquisition system of this pyrometer consisted of two parts: a slow system for obtaining reference data and a fast system to obtain data during pulse experiments. The digital data were captured directly into the computer core memory, where the data were treated by software routines in assembly language [17]. This system was shown to capture 13 000 measurements per second.

For conditions such that the total experimental time is less than 1 ms [18], even faster responses were required. Coslovi *et al.* [19], reported responses to a step input of 5 μs. Certain stringent design criteria in 1979 on the design and evaluation of a pyrometer with a response-time, were used to match the signal-to-noise ratios of the detector and the pre-amplifier to prevent the distortion of the signal. The pyrometer could be used in both visible and infrared regions of the spectrum, through the use of appropriate interference filters with bandwidths of ≈80 nm. The temperature range capability of the pyrometer was extended by introducing standard neutral density filters in the target path. A much faster way to extend the temperature range was suggested [19] in which the feedback resistance of the detector amplifier was automatically changed when the signal reached a pre-determined level. This automatic scaling-down could be achieved within the response-time constraints of the instrument. Calibration procedures developed for a millisecond pyrometer [17] were extended to incorporate procedures for the submicrosecond model [15].

Foley *et al.* [20] designed a two-colour pyrometer with a microsecond response-time for measuring temperatures between 2000 and 6000°. The pyrometer used a Si detector and incorporated high-speed automatic gain switching of linear amplifiers which yielded a high resolution, was highly stable and offered a wide temperature range to be measured.

The current of the photodiode detector in each channel was given by

$$i = 2kNA\omega c\int \beta(\lambda)\left[\lambda^4\left\{\exp(C_2/\lambda T) - 1\right\}\right]^{-1} \mathrm{d}\lambda \tag{1}$$

where k is the ratio of the international coulomb to the electronic charge $(=1.5922\cdot10^{-19})$, N is the quantum efficiency of the detector and was assumed to be 1, A is the target area $(=1.96\cdot10^{-3}\ \mathrm{cm}^2)$, ω is the solid angle at the target $(=0.041\ \mathrm{sr})$, c is the speed of light, $\beta(\lambda)$ is the transmission of the pyrometer optics at the specified wavelength in cm, and C_2 is Planck's second radiation constant (1.4388 cm·K). The product of the six constants in equation (1), collectively called k_1, is $7.677\cdot10^{-13}\ \mathrm{A\cdot cm^3}$. The actual current recorded by the pyrometer, on being exposed to incident radiation, was given by

$$B = k_2 i + B_o$$

where B_o was a zero offset value. So

$$B - B_o = k_1k_2S(\lambda, T) = k_3S(\lambda, T)$$

where $S(\lambda, T)$ is the result of the numerical integration of the Planck equation for the spectral transmission as measured for the channel concerned [20]. If the mean effective wavelength λ_{ef} [20], was used, then Eq. (1) could be approximated to yield the spectral radiance temperature T_1 (i.e. the temperature of a perfect radiator).

$$T_1 = C_2/(\lambda_{ef}\ln[1 + k_4/(B - B_o)]) \tag{2}$$

where $k_4 = k_3\,\lambda_{ef}^{-4}$ is the effective bandwidth of the channel. An iterative procedure was then used to check the accuracy of Eq. (2). The colour temperature (or the temperature of a blackbody whose spectral distribution approximates that of a real body) was then determined by taking the ratio of the spectral radiance, at effective wavelengths λ_1 and λ_2, of a blackbody at temperature T_c for the two channels

$$T_c = (\lambda_1 - \lambda_2)\,[\,(\lambda_1/T_2) - (\lambda_2/T_1)\,]$$

A detailed description of the calculation of the spectral transmission, the mean effective wavelength, calibration and accuracy was given [20]. The response time of the pyrometer was claimed to be 1.75 μs.

A three-colour pyrometer, which was claimed to lead to greater accuracy of the measured temperature, has been reported [21]. The incoming radiation was split, filtered and passed into three separate logarithmic photometer circuits. A summing matrix converted the three signals from the detectors into a log signal and the temperature was calculated from the following expression

$$T = A_1\,[\,\ln(RB/G^2) + A_2\,]^{-1}$$

where A_1 and A_2 are constants and R, B and G are voltages which are proportional to blackbody intensities for the appropriate wavelengths chosen.

Dils [22] developed a high-temperature optical fibre thermometer (now available commercially [23]) for use from 600° to approximately 2000°. A thin film of a precious metal or alloy was sputtered on to the end of a thin (0.25 to 1.25 mm diameter) sapphire optical fibre forming an effective small blackbody cavity. The sapphire fibre (m.p. 2050°) was then connected to a lower temperature glass fibre and hence to a suitable detector. The radiance emitted from the cavity in a narrow wavelength band was then used to measure the temperature of the surroundings in which the fibre tip was inserted. The modification of the basic theory required for the finite dimensions of the cavity, and the corrections for reflection within the fibre and at connections and ends are described [22]. At temperatures above 1100°, scattering, adsorption and reemission of radiation at imperfections and impurities in the fibre can be a problem and high quality sapphire crystals have to be used. The accuracy of temperature measurements was reported [22] to be 0.2% at 1000° and the repeatability 0.05%.

Calibration

Primary sources for calibration of pyrometers usually consist of a heated cavity [8, 10] with a small hole through which radiation can escape. Secondary sources include tubular filaments [24], open-wedge strip filaments [25], or sources in the shape of a cone [26]. Both primary and secondary sources are. however, not good working standards because they are expensive, cumbersome, have limited temperature ranges and are susceptible to drift in their intensities with time. The usual working standards are ribbon filament lamps [27]. Their advantages include a stable radiant intensity output, higher maximum attainable temperatures, and instantaneous heating of the filament. The lamp filament must be calibrated against a standard. Curves of emittance of tungsten lamps against wavelength are available [28].

Calibration errors depend on the means used to calibrate the pyrometer, the frequency of calibration, the drift rate of the system and the uncertainty in the knowledge of ε [27]. The use of the actual source-body for the calibration yields fewer errors and less uncertainty [29].

Applications

Pyrotechnic reactions

The recording of temperature-time profiles, in which thermocouple wires are used as temperature sensors, has become a well-used method for studying the burning of pyrotechnic compositions [4–7]. The range of compositions which can be studied is, however, limited to those where the maximum reaction temperature is below that of the melting point of the thermocouple material. Thermocouples (Ir, 40%, Pt/Pt, 40% Rh) capable of measuring up to 1900° in oxidizing conditions, and to higher temperatures [26] in reducing conditions [30], have been reported. The oxidizing conditions associated with the burning of pyrotechnic compositions impose a further limitation on the choice of thermocouples.

Where reaction conditions are too severe for the satisfactory use of thermocouples, radiation or infrared pyrometry may be used for the measurement of temperature [31]. Temperature measurements of 18 000° have been reported [32] in studies involving the measurement of temperature profiles of thermal plasmas. Since infrared pyrometry can only be used to measure surface temperatures, heat losses from the surface should not be excessive and measurements should be taken from a small area of surface so that temperature distributions can be resolved. Some of the inherent difficulties of radiation pyrometry, such as the change in the emittance of a sample, may be reduced if a ratio pyrometer is used and grey-body conditions are assumed. By careful design of the sample-holder and detector-assembly, excessive heat losses may be kept in check.

Some of the requirements for the application of pyrometry to the measurement of temperature-time data for burning pyrotechnics are: i) response-time of the instrument should be less than the rise-time to maximum temperature of a burning composition (i.e. at least less than 0.1 milliseconds), ii) the working temperature-range should be large (400 to 3000°), iii) the target area should be small so that the temperature variation across the target area is negligible, and iv) the instrumental drift from calibration should be small.

Silicon photodiode detectors with matching amplifiers with sub-microsecond response times are available commercially and are capable of measuring temperatures from 400 to 3500° in a single range, provided that the programmable amplifiers and the data acquisition systems are suitably matched [17]. Small target diameters may be examined, but, the smaller the target area, the poorer the signal-to-noise ratio.

An Ircon Modline II series 220 model infrared pyrometer, with a Si detector (bandpass centered around 0.9 μm) capable of measuring from 600 to 3000°, was used to measure the reaction temperature of Si/PbO compositions [33]. The pyrotechnic composition was packed into a delay element tube which was fitted into a detonator-tube. The open end of the detonator tube was fitted with a Perspex plug. The pyrometer was then focussed on the end of the delay composition through the Perspex plug and the composition was ignited from the other end. The reaction temperatures [33] of various compositions, predicted from thermodynamic data, were compared with measured reaction temperatures. The pyrometer readings were corrected for the emittance of the sample, calculated from available data of the emittance of the products of reaction and from plots of measured burning-temperatures at various emittance settings. Measured reaction temperatures were lower than the predicted temperatures and this was attributed to excessive lateral heat-loss through the tube walls.

In a study of the transfer of combustion through an inert septum separating two coloumns of pyrotechnic material, Boddington *et al.* [34] used infrared pyrometry to measure the temperature of the surface of the septum. The response times, γ, of the pyrometers used were derived from the rise and decay portions of the signal when the instrument was exposed to a delta pulse of radiation. Response times of the order of 10 ms were found and temperatures were corrected using the relationship

$$T_{\mathrm{corr}} = T_{\mathrm{exp}} + \gamma\, \mathrm{d}T_{\mathrm{exp}}/\mathrm{d}t$$

The ease-of-ignition is an important parameter in assessing the performance of a pyrotechnic material. The usual method of measuring the stimulus level required for ignition, using single samples under a given set of firing conditions, does not supply sufficient information on the performance under a wider range of conditions. An infrared scanner with sufficiently fast response-time (0.1 ms), was used to monitor the sample temperature during laser-induced ignition [35]. The heat content of a pellet of pyrotechnic material (assumed to be initially inert) on irradiation, can be calculated from the observed temperature distribution $T(r)$ using the equation

$$Q = 2\pi\rho C_p \int_0^R T(r)\, r^2 \mathrm{d}r$$

where Q is the total heat content, r is the radial distance and R the pellet radius, ρ is the density and C_p the heat capacity of the pellet. If a laser is considered to be a point source with heat flux q, the surface temperature at the centre of a spot $r<\mathrm{a}$ (where the heated spot size is $\pi \mathrm{a}^2$), is given approximately by

$$\Delta T = T_t - T_0 = (2q/\rho C_p \pi)\, t/D$$

where t is the time interval of exposure to laser, T_o is the initial temperature and D id the thermal diffusivity of sample. The above expression applies to samples only during the pre-heated period [34]. Curves of maximum temperature rise and the integrated total heat absorbed with time, allowed the activation energies for ignition of the compositions to be calculated using the equation

$$\mathrm{d}Q/\mathrm{d}T = Z \exp(-E_a/RT)$$

where Z is the Arrhenius pre-exponential factor and E_a the activation energy. The pyrometer used in this study was an Inframetrics Model 525. The analogue data signal was dumped onto a video recorder and digitized by an Interactive Video Systems Model 2000 digitizer interfaced to an Apple II microcomputer.

A similar study was conducted by Robertson and Igel [36] in which simultaneous cinematography and radiometry were used to record the onset and growth of ignition in pyrotechnic mixtures. An extensively modified Barnes Model RM–2A pyrometer, calibrated against a standard blackbody, was used. Temperature profiles of the ignition process were recorded on an oscilloscope, but these were not discussed in any detail.

In a recent study [37] of laser-induced ignition of pyrotechnics and explosives, an infrared detector array was used to determine the kinetics of these fast transient reactions. Samples of the explosive material were deposited as thin films (0.01 to 0.1 μm) on a substrate foil (25 to 50 μm thick) and temperature measurements were made on the underside of the foil on the assumption that the temperature of the foil was the same as that of the reacting material during the experiment. Because temperature measurements were made on the foil, uncertainties due to the changing emittance of the sample during reaction were minimized. No further details of the temperature sensing apparatus were discussed.

Hillenbrand and Shortridge [38] used an optical multichannel analyser to record the spectra from pyrotechnic flares. Estimates of the flame temperatures were obtained by fitting the Planck distribution to the background continuum radiation. Temperatures found were from 2900 K to 3300 K for various coloured flares based on magnesium as fuel. Similar values for combustion temperatures were estimated from detailed analysis of the rotational-vibrational transitions in the high resolution infrared spectra of CO_2 in the combustion products.

Hussain and Rees [39] used FTIR-emission spectroscopy to study the combustion of blackpowder. Most emphasis was on the identification of combustion products, but by observing the combined emission from a blackbody source and the flame, the temperature of the flame was determined to be in excess of 1540°. This was higher than the maximum combustion temperatures of $\approx$1400° measured using a conventional thermocouple [40].

Shock-wave research

Radiation pyrometry has been used to measure the temperature distribution of the surfaces of inert materials [41], liquids and explosives [42] on exposure to detonic shock waves, or on collision with high-velocity projectiles [43]. The response times of the pyrometers used in the above applications were of the order of 0.5 μs and were thus appreciably slower than the rise time (of a few nanoseconds) of the shock waves [44]. The use of visible pyrometry for shock wave research, was reported to require high degrees of illumination from the source-body and thus only high temperatures could be measured [45]. The detection system used by Von Holle *et al.* [43] initially consisted of two independently operated pyrometers with InSb (2 to 5.5 μm) and HgCdTe (5 to 11 μm) photovoltaic detectors. The independent detector signals were amplified by wide-band video amplifiers (rise time 4 ns) and the signals were recorded by fast digital or analogue oscilloscopes. The pyrometers were calibrated against a 200 to 1000° blackbody source. The above system was subsequently modified [46] to incorporate two InSb detectors which were set up in identical geometries, with suitable filters, such that the pass bands overlapped (2 to 5.5 and 4 to 5.5 μm). The detected emittance was then given by

$$W_{\mathrm{det}} = \varepsilon_{\mathrm{band}} \int W_{\mathrm{bb}}(\lambda, T)\, d\lambda$$

where $\varepsilon_{\mathrm{band}}$ is the band emittance and W_{bb} is the integrated Planck function. For the two pyrometers then, in a two-colour configuration, the ratio of the detected radiant power depended on the ratio of the integrated blackbody responses. The response time of the instrument was reported to be approximately 10 ns. The results of these studies provided direct evidence for the formation of hot-spots and provided reaction histories and rate data for reaction induced by shock initiation [46].

Thermal imaging

Infrared thermography is used extensively to provide thermal images, in several applications, for the detection of objects not normally visible to the eye [47]. Infrared detectors housed in video cameras may be linked to a microcomputer and printer, or to a standard video recorder. The resolution provided by such cameras can be of the order of 0.1°.The ranges in which temperatures may be measured are usually −20 to 500° and from 500 to 1500°. The spectral response of these instruments is from 2 to 14 μm, and the response-times are of the order of 250 to 400 ms. Thermal imaging is widely used for the detection of wear in the refractory-lining of furnaces, ladles and heated containers. In a recent study [48], an infrared camera system was used to determine transient heat fluxes to divertor plates in tokamak vessels. The camera pass band was 8 to 12 μm (for better accuracy at low temperatures) and the image was stored on a standard video tape. From surface temperature profiles as a function of time, the incident heat flux could be estimated. Comparison with two-dimensional finite-element computer simulations, using the analysis code TOPAZ [49], gave good agreement [50].

Thermophysical properties

The optical absorption, thermal diffusivity and related properties of opaque materials have been studied using opto-thermal transient emission radiometry [51]. The technique consists of measuring the infrared radiation emitted from a surface, previously heated by a laser pulse, as the temperature of the surface decays to a steady-state condition, The properties of the sample are then determined from an analysis of the transient emission curves [52]. This technique has been modified by incorporating monochromators which allow wavelength-selective detection, so that the effects associated with the absorption of radiation can be separated from the emission from the heated surface [53].

A high-speed pyrometer [19] has been used in the determination of thermo-physical properties such as heat capacity, electrical resistivity, melting temperature, temperature and energy of solid-solid phase transformations, heats of fusion and thermal expansion of various metals and non-metals [54] in temperature ranges which are not normally accessible.

Conclusions

Significant progress has been made in the use of pyrometry to study rapidly changing high-temperature processes. Temperatures, which have largely been inaccessible to classical measuring devices, can be measured using pyrometry and the technique has been additional advantage of being non-intrusive. Pyrometers with very fast response times (10 ns) have been designed and constructed for specific experiments. Where accurate temperature measurements are to be made, knowledge of the emittance of the sample as well as the way in which the emittance varies with temperature, is essential. Ratio pyrometers have gone some way towards solving this problem. The processing of the pyrometer detector signal, however, is usually complex and rapid data acquisition systems are needed for real time processing.

Pyrometry has been increasingly used in the study of high-temperature transient events like the ignition of pyrotechnic and explosive materials. Because of the extreme redox conditions associated with burning of explosives and with pyrotechnic material in particular, the remote sensing capabilities of pyrometers should enable temperature-time measurements to be made, even allowing for the increased uncertainties, under conditions formerly inaccessible.

There are some significant limitations inherent in the technique. Pyrometers which can accurately cover the full range from ambient to very high temperatures are not available. Thus information on the lower temperature region, if required, has to be obtained using other techniques and the results merged with those for the higher temperature range. Temperature measurements are restricted to surfaces so that information of the processes occurring within the bulk of the sample has to be inferred where possible. There are also the problems of heat-loss from the surfaces and the resolution of the temperature differences across a surface. When the surface is also involved in chemical reactions, there may be complications of absorption of radiation by gaseous or particulate products.

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Zusammenfassung — Es wird ein Überblick über die theoretischen Grundlagen der Anwendung von Pyrometrie bei der Untersuchung von schnellen Prozessen mit schnellen Temperaturänderungen in ursprünglich festen Proben gegeben. Die verschiedensten Pyrometer werden kurz beschrieben und ein Überblick über ihre Anwendung bei der Untersuchung von pyrotechnischen Reaktionen, bei der Stoßwellenforschung und bei der Messung thermophysikalischer Größen wird gegeben.