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New Facilities for the Measurements of High-Temperature Thermophysical Properties at LNE

Bruno Hay · Jacques Hameury · Nolwenn Fleurence · Pascal Lacipiere · Marc Grelard · Vincent Scoarnec · Guillaume Davee

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Abstract LNE is expanding the measurement capabilities of its metrological platform devoted to the determination of the main thermophysical properties of materials toward very high temperatures. In particular, two facilities have been developed for measuring the directional spectral emissivity up to 1500 °C and the thermal diffusivity up to 3000 °C in the case of homogeneous solid materials and of thermal barrier coatings. These developments have required in particular the design of specific heating systems which are based either on the use of a lamp image furnace or on inductive heating technology. These works are performed in the framework of two international projects related to the thematic "Energy", and which involve essentially European national metrology institutes. The availability of reference metrological facilities for the characterization of thermophysical properties of materials at high temperature with controlled uncertainties will enable ultimately the improvement of the traceability in academic and industrial research laboratories for measuring these quantities. This paper gives a detailed description of these metrological facilities and of the associated measurement methods.

Keywords Emissivity · High temperature · Metrology · Thermal diffusivity

1 Introduction

The improvement of the energy efficiency of thermal and nuclear power plants often involves an increase of operating temperatures (up to 1500 °C for gas turbines or for some Generation IV nuclear reactors). These high temperature levels require the

B. Hay (✉) · J. Hameury · N. Fleurence · P. Lacipiere · M. Grelard · V. Scoarnec · G. Davee
Laboratoire National de Metrologie et d'Essais, Laboratoire Commun de Metrologie (LNE-LCM), Scientific and Industrial Metrology Centre, 1 rue Gaston Boissier, 75015 Paris, France
e-mail: bruno.hay@lne.fr

implementation of advanced materials with known thermal behaviors. It is thus essential to accurately determine their thermophysical properties (thermal transport, caloric, and radiative properties) at temperatures close to those encountered in real situations, including, for example, accident conditions in fission reactors (up to several thousands of degrees Celsius). Some thermal properties of materials are already measured at very high temperatures by research institutes using dedicated facilities (in the nuclear field especially) [1–6]. The measurement methods used by these institutes require reference materials certified up to 2000 °C as a minimum, either for the validation of absolute measurement techniques or for calibration of comparative ones (e.g., thermal analysis techniques). The reference materials need in particular to have thermophysical properties in the same range as the investigated materials and to be stable at the temperatures of use. For a lot of thermophysical properties, there is currently no possibility in Europe of ensuring the traceability of these measurements to the SI above 800 °C, due to the temperature range limitation of the metrological reference facilities available in European national metrology institutes (NMIs) and to the lack of suitable reference materials.

Since 2010, LNE has worked in the improvement of the measurement capabilities in terms of temperature range of its metrological platform devoted to the measurement of the main thermophysical properties of materials, such as thermal conductivity, thermal diffusivity, specific heat, and emissivity of solid materials. These works are performed in the framework of the two following European joint research projects: "MetroFission" [7] and "Powerplant" [8]. The first project entitled "Metrology for new generation nuclear power plants " aims to contribute to knowledge and technologies required for the development, construction, and operation of the next generation of nuclear power plants, by offering to improve the metrology of temperatures, and thermophysical properties of materials and ionizing radiation for this type of application. The second project entitled "Metrology for improved power plant efficiency" focuses both on the metrological research needed to reduce the measurement uncertainties of the important control parameters (temperature, flow, thermal energy, and electrical output) of power plants, and on the improvement of the thermal characterization of advanced materials (refractory alloys and thermal barrier coatings) to be used in future gas turbines. These two projects lasting three years each, began in September 2010, and are jointly funded by the European Commission and the participating countries within European Association of National Metrology Institutes (EURAMET) under the "European Metrology Research Program" (EMRP). In the two projects, LNE is leading the work packages dedicated to the characterization of the thermophysical properties of materials. The overall objective of these work packages is to develop and improve metrological facilities for measuring thermophysical properties of materials up to at least 1500 °C with controlled uncertainties of measurement. Two other European national metrology institutes, National Physical Laboratory (NPL, UK) and Physikalisch Technische Bundesanstalt (PTB, Germany) contribute also to these work packages. Figure 1 gives an overview of the capabilities of LNE in terms of thermophysical properties characterization, compared with the needs of main industrial applications. The black and grey rectangles represent, respectively, the current measurement capabilities of LNE and the new developments.

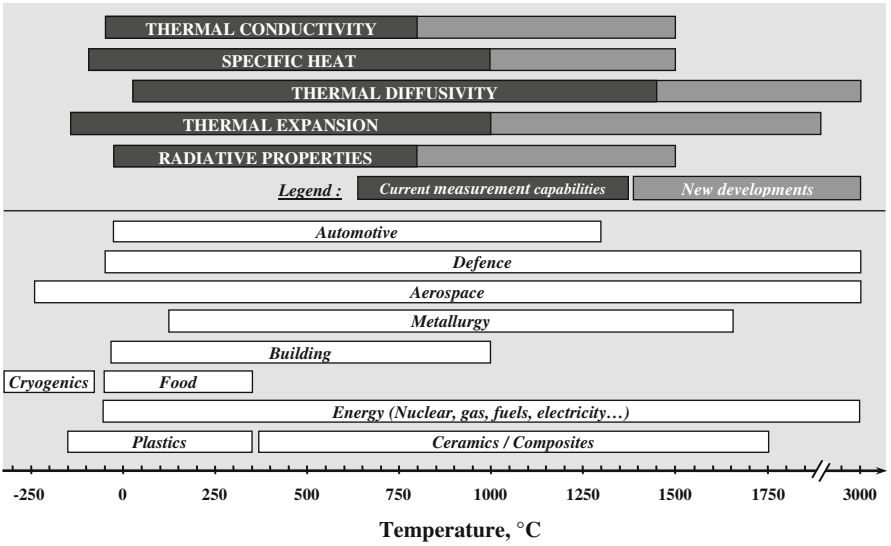

Fig. 1 Measurement capabilities of LNE for the characterization of thermophysical properties

This paper gives a detailed description of the metrological facilities and measurement methods which have been developed very recently at LNE for the measurement of the thermophysical properties of solid materials at very high temperature (up to 3000 °C for thermal diffusivity).

2 Spectral Emissivity Measurements of Solid Materials up to 1500 °C

2.1 Previous Measurement Capabilities

As a national metrology institute, LNE has developed and improved since two decades facilities based on absolute methods for measuring the following radiative properties of materials in the infrared spectrum.

- Total hemispherical emittance from −20 °C to 200 °C [9],
- Directional spectral emittance from 23 °C to 120 °C in the spectral range from 1 μm to 14 μm for five angles of incidence (12°, 24°, 36°, 48°, 60°) [10],
- Spectral normal emittance from 200 °C to 850 °C in the spectral range from 2.5 μm to 13 μm [11].

The measurement capabilities of the LNE's existing "high-temperature" facility are limited to 850 °C (for good thermal conductors). The spectral selection is made by interference filters having a relatively large bandwidth, which does not enable detection of the spectral variations of emissivity of materials whose spectral emissivity varies strongly (see example of silicon carbide in Fig. 2). The technique used to measure the surface temperature (measurement of two temperatures at two positions in the thickness of the specimen, and calculation of the surface temperature by extrapolation)

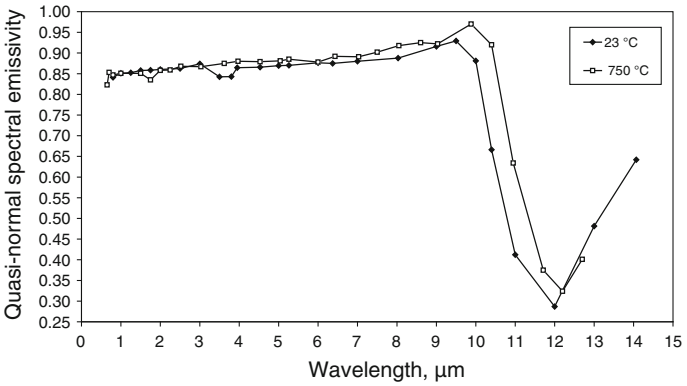

Fig. 2 Spectral emissivity of silicon carbide (measured by LNE) used in the cavity of the reference blackbody

imposes significant restrictions on the specimen geometry (no possibility to perform measurements on thin specimens).

2.2 New Developments

For these reasons, LNE launched the development of a new facility for measuring the spectral directional emissivity up to 1500 °C in the spectral range from 0.8 µm to 10 µm with a spectral resolution of 1 cm^{-1}. The aim is to be able to measure this radiative property with a relative uncertainty of measurement of around 2 % for high emissivities and for temperatures higher than 800 °C.

2.2.1 Method of Measurement

The measurement method is directly based on the definition of the spectral directional emissivity. The general principle consists of the comparison of the spectral radiance of the specimen at a temperature T to that of a blackbody reference at the same temperature, the directional spectral emissivity of the specimen being equal to the ratio of these two quantities.

Figure 3 shows a general scheme of the facility. The main elements are the following: a reference blackbody, a heating system enabling the specimen (typically disk of 25 mm in diameter and 10 mm thick) to be heated up to 1500 °C in an inert atmosphere, a blackbody at room temperature (named cold blackbody in the rest of this paper) for the correction of background radiation, an optical system for collecting the radiation emitted by the specimen or the blackbodies, and a Fourier transform spectrometer which acts as a spectroradiometer. Radiation sources (blackbodies and specimen heating system) move laterally, in order to be positioned in front of the radiation measurement system (spectrometer and optical system). This one is maintained in a fixed position in order to avoid any variation of sensitivity. The radiometric signals measured successively on the reference blackbody $V_{rb}(\lambda)$, the specimen $V_s(\lambda)$, and the cold blackbody $V_{cb}(\lambda)$ can be written for each wavelength as follows:

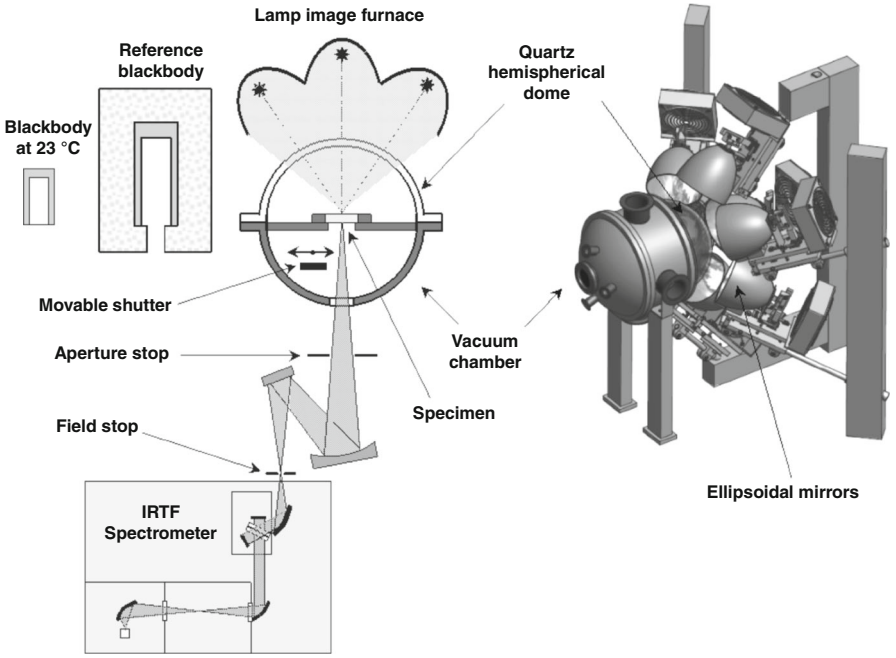

Fig. 3 Schematic of the new LNE facility for the measurement of directional spectral emittance at high temperature

$$
\begin{aligned}
V_{\mathrm{rb}}(\lambda) &= K\left[S_{\mathrm{d}}(\lambda)\tau_{\mathrm{atm}}(\lambda)\left[\varepsilon'_{\mathrm{rb}}(\lambda, T_{\mathrm{rb}})L^{\circ}_{\lambda}(T_{\mathrm{rb}}) + (1-\varepsilon'_{\mathrm{rb}}(\lambda, T_{\mathrm{rb}}))L^{\circ}_{\lambda}(T_{\mathrm{RT}})\right] + S_{\mathrm{offset}}\right]\\
V_{\mathrm{cb}}(\lambda) &= K\left[S_{\mathrm{d}}(\lambda)\tau_{\mathrm{atm}}(\lambda)\left[\varepsilon'_{\mathrm{cb}}(\lambda, T_{\mathrm{cb}})L^{\circ}_{\lambda}(T_{\mathrm{cb}}) + (1-\varepsilon'_{\mathrm{cb}}(\lambda, T_{\mathrm{cb}}))L^{\circ}_{\lambda}(T_{\mathrm{RT}})\right] + S_{\mathrm{offset}}\right]\\
V_{\mathrm{s}}(\lambda) &= K\left[S_{\mathrm{d}}(\lambda)\tau_{\mathrm{atm}}(\lambda)\left[\tau_{\mathrm{wind}}(\lambda)\left[\varepsilon'_{\mathrm{s}}(\lambda, T_{\mathrm{s}})\cdot L^{\circ}_{\lambda}(T_{\mathrm{s}}) + (1-\varepsilon'_{\mathrm{s}}(\lambda, T_{\mathrm{s}}))L^{\circ}_{\lambda}(T_{\mathrm{RT}})\right]\right.\right.\\
&\quad \left.\left. + (1-\tau_{\mathrm{wind}}(\lambda))L^{\circ}_{\lambda}(T_{\mathrm{RT}})\right] + S_{\mathrm{offset}}\right],
\end{aligned}
$$

where K is the sensitivity of the spectroradiometer taking into account the measurement spot size and the beam aperture, λ is the wavelength, L°_{λ} is the spectral radiance calculated from Planck's law, T_{RT} is the room temperature; T_{rb}, T_{s}, and T_{cb} are, respectively, the temperatures of the reference blackbody, of the specimen surface, and of the blackbody at room temperature (assumed to be equal to T_{RT}), $S_{\mathrm{d}}(\lambda)$ is the spectral sensitivity of the spectroradiometer, $\tau_{\mathrm{atm}}(\lambda)$ is the spectral transmittance of air along the optical path, $\tau_{\mathrm{wind}}(\lambda)$ is the spectral transmission of the window of the vacuum chamber, S_{offset} is the offset signal of the spectroradiometer, and $\varepsilon'_{\mathrm{rb}}$, $\varepsilon'_{\mathrm{cb}}$, and $\varepsilon'_{\mathrm{s}}$ are, respectively, the directional spectral emissivities of the reference blackbody, of the cold blackbody, and of the specimen surface. The spectral emissivities $\varepsilon'_{\mathrm{rb}}$ and $\varepsilon'_{\mathrm{cb}}$ of the blackbodies are calculated using the radiosity technique considering the distribution of temperature along the cavity. The distribution of temperature was measured using a thermocouple traveling in a groove along the cavity.

The following parameters are assumed to be constant for the three successive radiance measurements: the spectral sensitivity of the spectroradiometer $S_{\mathrm{d}}(\lambda)$, the factor K, the spectral transmittance of air along the optical path $\tau_{\mathrm{atm}}(\lambda)$, and the offset signal

of the spectroradiometer S_{offset}. The window is assumed to be isothermal at room temperature, and its emissivity is considered to be equal to its absorption factor given by relation $\alpha_{\text{wind}}(\lambda) = 1 - \tau_{\text{wind}}(\lambda)$. The temperature of the cold blackbody is very close to the room temperature, and the window is assumed to be at a uniform temperature equal to room temperature. The combination of the three preceding relations leads to the following equation giving the directional spectral emissivity of the specimen as a function of the measured parameters [11]:

$$\varepsilon'_{\text{s}}(\lambda, T_{\text{s}}) = \frac{V_{\text{s}}(\lambda) - V_{\text{cb}}(\lambda)}{V_{\text{rb}}(\lambda) - V_{\text{cb}}(\lambda)} \cdot \frac{\varepsilon'_{\text{rb}}(\lambda, T_{\text{rb}})}{\tau_{\text{wind}}(\lambda)} \cdot \frac{L^{\circ}_{\lambda}(T_{\text{rb}}) - L^{\circ}_{\lambda}(T_{\text{cb}})}{L^{\circ}_{\lambda}(T_{\text{s}}) - L^{\circ}_{\lambda}(T_{\text{cb}})}. \tag{1}$$

2.2.2 Description of the Apparatus

The spectral radiances of the specimen and of the blackbodies are measured with a Fourier transform infrared spectrometer (Vertex 70 manufactured by Bruker). An optical system (composed of a flat mirror, a spherical mirror with a curvature radius of 1 m, a field stop, an aperture stop, and baffles) is used to collect the radiation emitted by the source (blackbody or specimen) by keeping constant the measurement spot size and the numerical aperture. The spherical mirror forms the image of the field stop, located at the entrance of the spectrometer, in the plane corresponding to the surface of the specimen or to the entry of the blackbody cavities. The field stop defines the size of the surface analyzed on the specimen, and the aperture stop defines the entrance pupil of the optical system. The operating validation of the spectrometer for the radiance measurements was done by comparative measurements performed on two blackbodies. The size-of-source effect of the spectroradiometer was also measured in order to define the real size of the measuring field. The reference blackbody is equipped with a silicon carbide cavity which can be used in a large spectral range from 0.8 μm to 10 μm. The temperature of the reference blackbody is measured with a type S thermocouple or a pyrometer.

The emissivity measurement by the radiance comparison method requires that the tested surface is not submitted to a significant incident radiation in the spectral range of measurement. It is indeed not possible to identify separately the component of the radiation emitted by the specimen to that of the reflected incident radiation. Consequently, the specimen cannot be heated in a "closed " oven, where all its faces would be irradiated by the heater elements; the specimen must be heated only through the rear face or the edges. The radiation flux density lost by the front surface of the specimen is so high (up to $56\,\text{W} \cdot \text{cm}^{-2}$ at 1500 °C) that it is very difficult to supply enough heat with a classical electrical resistor. The solution selected by LNE is to use a lamp image furnace (cf. Fig. 3), where heat is produced by a set of seven halogen lamps (400 W each), and is focused on the rear side of the specimen with ellipsoidal mirrors. This technique was chosen because makes it possible to heat quickly to 1500 °C specimens with different sizes and different geometries.

The specimen is heated in a vacuum chamber with a controlled atmosphere to avoid oxidation at high temperature. The chamber has a quartz hemispherical dome transparent to the radiation of the lamps. Radiance measurements on the front face of the specimen are made through a CaF_2 or a ZnSe window depending on the wavelength

range (ZnSe beyond 9 μm). The walls of the chamber are water cooled and coated with a high emissivity paint in order to control the background radiation on the front face of the specimen. A thermostated movable shutter limits the heating of the window during the measurements of the spectral radiances of the blackbodies. The surface temperature of the specimen, which is a critical parameter of the measuring method of emissivity, can be measured by contact thermometry (for thick specimen having high thermal conductivity), bichromatic pyrometry, or by the "pyroreflectometric" technique.

2.2.3 Description of the Pyroreflectometric Technique

The principle of the pyroreflectometric technique [12,13] is based on the measurement of spectral radiances of a surface at two wavelengths, λ_1 and λ_2, close to each other, and on the measurement of the ratio of directional–directional spectral reflectances at both wavelengths. Considering the assumption that the angular diffusion of the surface is the same for both wavelengths, it is possible to compute the surface temperature of the target and the directional spectral emissivities at the two wavelengths, from the measured spectral radiances and the ratio of the bi-directional spectral reflectances at the two wavelengths. The optical arrangement is schemed in Fig. 4. The pyroreflectometer of LNE is basically composed of a bichromatic detection module, a bichromatic emission module, and two optical systems made of a multimode optical fiber and an objective. The emission module uses two pulsed laser diodes at 1310 nm and 1550 nm to generate an incident beam for spectral reflectance measurements. Two InGaAs photodetectors are used in the detection module to measure the optical power gathered by the detection objective. The light is shared between the two channels by a semi-transparent beam splitter. Two bandpass interference filters (centered approximately

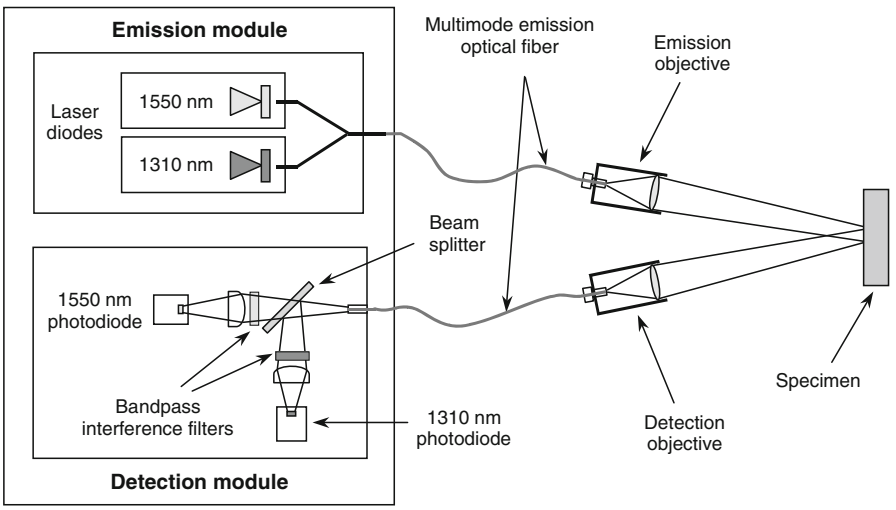

Fig. 4 Diagram of the pyroreflectometer

around 1310 nm and 1550 nm) are used to define the spectral bands of the detection system. The objectives use one lens, and the output section of the fiber is directly imaged on the surface of the specimen. The size of the field defined by each objective on the specimen surface is defined by the diameter of the fiber and the distance from the fiber end to the lens. The detection module can be used as a bichromatic spectral radiance meter after calibration using a reference blackbody. The pyroreflectometer can be used as a bi-directional spectral reflectometer, using the detection and emission modules. The pyroreflectometer is calibrated in order to determine the following parameters:

- the sensitivity of the detection module for the measurement of spectral radiances at the two wavelengths,
- the sensitivity of the pyroreflectometer for the measurement of the ratio of the directional–directional spectral reflectances at the two wavelengths.

The relative spectral sensitivities of the two channels of the detection module were measured using a facility developed by LNE for the calibration of infrared detectors. For spectral radiance measurements, the pyroreflectometer is calibrated using blackbodies that are traceable to primary reference standards through the use of calibrated thermocouples or pyrometers. Figure 5 shows that the responses of the detection module versus spectral radiance are very linear on both channels. The relative gap from a linear response is below 0.15 %. For the measurement of the ratio of the directional–directional spectral reflectances at the two wavelengths, the "reflectometer" is calibrated by using a reference sample calibrated on the quasi-normal hemispherical spectral reflectance. The reference sample is made of a very reflecting and diffuse material. When measuring the surface temperature of a target, the two spectral radiances that are measured for the two wavelengths are given by

$$L_{\lambda_1}(T_s) = \varepsilon'_s(\lambda_1, T_s) L^{\circ}_{\lambda_1}(T_s) \tag{2}$$

$$L_{\lambda_2}(T_s) = \varepsilon'_s(\lambda_2, T_s) L^{\circ}_{\lambda_2}(T_s), \tag{3}$$

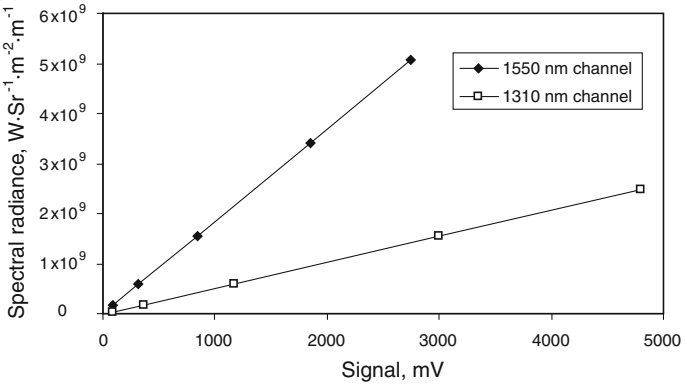

Fig. 5 Spectral radiance as a function of the signal delivered by the detection module of the pyroreflectometer

where $L^{\circ}_{\lambda}(T_s)$ is the spectral radiance of a blackbody at temperature T_s (given by Planck's law). The background radiation is neglected considering that the surface temperature of the target is quite high (over 500 °C). For those measurements the lasers are turned off.

The directional/directional spectral reflectances measurements are then performed successively for the two wavelengths, one at a time. For the selected wavelength, the laser diode is turned on and a signal proportional to the thermal spectral radiance of the target (Eq. 2) plus the spectral radiance due to the reflection of the laser beam is measured. The signal proportional to the reflection of the laser beam is calculated by subtracting the signal measured with the laser diode "off" from the signal measured with the laser diode "on." The directional/directional spectral reflectance measurements are performed exactly for the same geometrical conditions for the two wavelengths, λ_1 and λ_2 (same directions of incidence and of reflection, same geometrical apertures). The ratio of the two signals related to the reflections of the laser beams is then proportional to the ratio of the directional/directional spectral reflectances at the two wavelengths. All the measurements are synchronized by a clock driving the laser diodes and the measurements of signals. The assumption of the pyroreflectometry technique is that the relative angular diffusion of the surface of the target is the same for the two wavelengths because the wavelengths are close. This assumption can be written as

$$\frac{\rho''(\lambda_1, T_s)}{\rho''(\lambda_2, T_s)} = \frac{\rho'^{\cap}(\lambda_1, T_s)}{\rho'^{\cap}(\lambda_2, T_s)} = \frac{1 - \varepsilon'_s(\lambda_1, T_s)}{1 - \varepsilon'_s(\lambda_2, T_s)}. \tag{4}$$

The system of Eqs. 2 to 4 can be solved numerically to get the three unknown parameters: the surface temperature T_s and the directional spectral emissivities $\varepsilon'_s(\lambda, T_s)$ at the two wavelengths, λ_1 and λ_2. The pyroreflectometer can also work as a "classical" bichromatic pyrometer by assuming that the spectral emissivities of the material at the two wavelengths, λ_1 and λ_2, are equal.

3 Thermal Diffusivity Measurement of Solid Materials and Coatings up to 3000 °C

3.1 Previous Measurement Capabilities

LNE has performed for many years thermal diffusivity measurements of homogeneous materials up to 1400 °C in argon or vacuum environments by using a homemade facility [14] based on the "traditional" principle of the *rear face* laser-flash method [15]. In this method, a cylindrical specimen is irradiated on its front face by a short energy pulse, and the induced transient temperature rise on its rear face is measured versus time. The thermal diffusivity is calculated by identification of the experimental temperature–time curve (thermogram) with a theoretical model. This primary absolute method allows measurements that are directly traceable to primary SI units (such as temperature, time, length, voltage, etc.) without any calibration using reference materials.

In the case of a bulk homogeneous material, the thermal diffusivity is estimated by LNE according to the "partial time moments method" [16], which takes into

account the heat losses between the sample and its surroundings. This identification method was notably used by LNE in the certification process of Pyroceram 9606 as BCR-724 reference material [17]. The relative expanded uncertainty ($k = 2$) on thermal diffusivity measurements of homogeneous materials by this method has been estimated to be between 3 % and 6 % over the temperature range of 23 °C to 1400 °C [18], depending on the material and the temperature level. This versatile apparatus enables one also to measure the thermal diffusivity of thick coatings having a thickness of a few hundred micrometers up to 800 °C, by applying the *front face* laser-flash method. The "partial time moments method", being not convenient for the study of coatings or multilayered materials, a specific identification procedure enabling thermal diffusivity evaluation of coatings by the *front-face* laser-flash method has been developed [19]. This method was applied up to 800 °C to the determination of the thermal diffusivity and thermal conductivity of chromium oxide coatings, a few hundred micrometers thick, deposited on a substrate of iron [20].

3.2 New Developments

In the original configuration, the operating temperature range of the facility was limited to 1400 °C (800 °C in the case of coatings), due in particular to the two resistive furnaces used. The setup has been therefore extensively modified to enable the measurement of the thermal diffusivity of homogeneous materials up to 3000 °C and of thick coatings up to 1400 °C under vacuum or inert atmosphere (argon or helium). For this purpose, a specific inductive furnace has been developed and fitted to the existing diffusivimeter, and the associated infrared detection systems and excitation source have been adapted. Figure 6 shows a schematic representation of the facility in the new configuration, modified parts being represented in gray. The short thermal excitation (around 450 µs) is generated by a Nd:phosphate glass laser at 1054 nm wavelength. A flat mirror located at the beginning of the laser beam path enables one to direct the beam towards the resistive furnaces or the inductive one. The beam is then formed by a set of lenses and mirrors so that its diameter is about 10 mm on the front face of the specimen. A photodiode is used to determine the duration, the form of the pulse, and the time origin that corresponds to the time when the laser beam irradiates the specimen.

The induction furnace is an enclosure cooled by water in the center of which an inductive coil and a movable susceptor are placed on a vertical axis. The inductor is a copper solenoid also cooled by water and connected to a 50 kW high frequency generator (100 kHz to 400 kHz). The susceptor is a hollow cylinder (molybdenum or graphite depending on the temperature range) with a shoulder machined at mid-height to maintain the sample (disk of 10 mm in diameter and 1 mm to 5 mm thick). The currents induced (Foucault currents) in the susceptor generate heat by the Joule effect. The specimen located inside the susceptor is heated primarily by radiative transfer. Due to a very low thermal inertia, the oven can heat a specimen very quickly at very high temperatures (from room temperature to 3000 °C in a few seconds). This furnace is equipped with two ZnSe windows, which are transparent to the laser

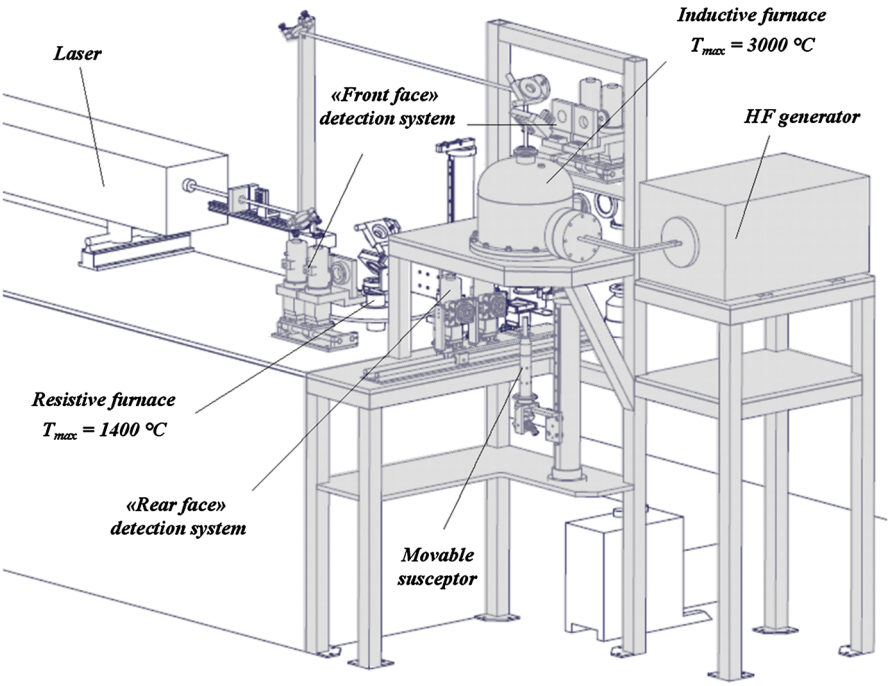

Fig. 6 Schematic diagram of the new LNE setup for the measurement of thermal diffusivity

wavelength and to the wavelength ranges of the IR detectors. The temperature of the specimen is measured, once steady, with an infrared bichromatic pyrometer (0.90 μm and 1.05 μm) having an operating temperature range covering that of the induction furnace. A specific IR detection system, enabling measurement of the temperature evolution of the front face at the location of the thermal disturbance, was designed and fitted to the existing high temperature resistive furnace, whose the working temperature range is from room temperature to 1400 °C. A similar system could be positioned above the inductive furnace in the future.

The induced temperature rise on the rear or front face of the specimen is measured optically with InGaAs and HgCdTe infrared detectors. An optical system made of lenses is associated to each IR detector in order to collect the infrared radiation emitted by the specimen. The bichromatic pyrometer (not shown in Fig. 6) and the infrared detectors are installed on a linear stage enabling one to put one or the other opposite the 90° flat mirror attached below the movable susceptor. The alignments of the optical elements (lenses, mirrors, diaphragms, etc.) are performed with a HeNe laser concentric with the Nd:phosphate glass laser beam. Specific amplification systems manufactured by LNE are associated to each detector in order to optimize the signal-to-noise ratio. A safety hood (not shown in Fig. 6) surrounds the laser beam over all the optical path, to avoid accidental injuries to the user.

3.3 Related Measurements: High-Temperature Thermal Conductivity

In the case of medium and high conductive materials (ceramics, metals, alloys, etc.), LNE performs the assessment of the thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$) by an indirect approach, from thermal diffusivity a ($m^2 \cdot s^{-1}$), density ρ ($kg \cdot m^{-3}$), and specific heat c_p ($J \cdot kg^{-1} \cdot K^{-1}$) measurements by means of

$$\lambda = a \rho c_p, \tag{5}$$

where the thermal diffusivity, density, and specific heat are, respectively, measured by the laser-flash method (see section above), by the immersion method, and by differential scanning calorimetry (DSC). Up to now, the thermal-conductivity measurement capabilities of LNE were limited to 800 °C due to the maximum working temperature of the used DSC. This temperature range will be increased to 1600 °C by using a new high temperature DSC (Setaram multi-HTC calorimeter). In addition, the thermal expansion of the studied material is measured as a function of temperature with a commercial push-rod dilatometer operating from 23 °C to 2000 °C. Expansion data are needed to calculate the corrections on the specimen thickness (measured at room temperature with a micrometer) which is used for the calculations of thermal diffusivity and density at high temperature.

4 Conclusion

LNE recently designed two reference metrological facilities for the measurement of the directional spectral emissivity up to 1500 °C and of the thermal diffusivity up to 3000 °C. The validation of these facilities is under progress, in particular, by measuring the thermal diffusivity and emissivity of tungsten and graphite at high temperature. The next step will be the assessment of the measurement uncertainties for these two quantities. The thermophysical properties of materials used in gas turbines (nickel-based alloys or yttria-stabilized zirconia coatings) or of non-active materials having similar properties as those used in Generation IV nuclear reactors will be measured in the near future with these new facilities in the framework of two European projects, “MetroFission” and “Powerplant”.

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