

INFRARED HEATING SYSTEMS COMBINED WITH CONTACTLESS MEASURING TECHNIQUES

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Abstract. *This paper describes the possibilities that result from the integration of infrared (IR) heating systems in material development, in the qualification accompanying the development, and in the processing of the material. Special emphasis is given to integrable measuring technology (temperature measurement, expansion and elasticity measurement, etc.) through which the processes can be exactly recorded and reproduced. Using several realistic examples from material processing as well as component qualification, the specific features will be illustrated.*

Key Words: *thermal measurements, IR radiation heating, drying, material processing*

1. INTRODUCTION

New applications under high-temperature and wearing conditions, especially in turbines and power plant operations, require materials having consistently higher performance capabilities. This high level of demand can only be reached through the integration of ceramic materials or their combination with metals. Thus, material development is often application-specific: high-temperature treatment steps during material production and processing are an absolute must. During material development, the characteristics of the material and the resulting components must be determined. Normally, these components are exposed to very high thermal gradients and transient conditions. In order to expose the components and samples to reproducible stresses, a suitable heating system is necessary. The highest surface densities of the radiant flux can be made on large surfaces with the help of IR radiation. The modularly arranged heating elements allow the radiation to be directly applied to the components to be examined.

The full performance capability is first reached, however, when the combination of the corresponding measuring techniques is realized. Innovative techniques in measuring temperature, emissivity, layer thickness, degree of dryness as well as expansion and elasticity are possible, especially when combined with IR heating technology. In this paper, the mo-

de of operation is presented using examples from material testing, and the possible integration with adjusted measuring techniques explained. A special emphasis is placed on the advantages that result from the combination with specific measuring methods. The operational principles of several measuring methods are described.

2 IR HEATING TECHNOLOGY

Electric IR heating systems were already developed in the 1930's for drying automobile chassis. Since that time, hundreds of IR applications have been installed, establishing themselves in many areas. The advantages for the use of IR technology in these areas are mainly:

- high heating rate and thus power density as well as high level of effectiveness
- compact shape of the module and components
- high flexibility in controlling and configuration
- consistent, reproducible quality
- anti-polluting, economical and low emissive heating.

3 CHARACTERISTICS OF IR RADIATION

The principle of heating uses a heated body (here special high-performance IR radiators) which radiates electromagnetic waves according to Planck's radiation law:

$$E_s \lambda = \frac{C_1}{\lambda^5} \cdot \frac{1}{e^{\frac{C_2}{\lambda T}} - 1} \quad [\text{W} / \text{m}^2 \cdot \text{m}], \quad (1)$$

$E_s \lambda$ – Black body radiation of a body at the wavelength λ ,

$C_1 = 3,741 \cdot 10^{-16} \text{ (W m}^2 \text{)},$

$C_2 = 1,439 \cdot 10^{-2} \text{ (m K)}.$

The radiation maximum shifts with increasing temperature towards shorter and shorter wave lengths, according to Wien's displacement law (Fig. 1).

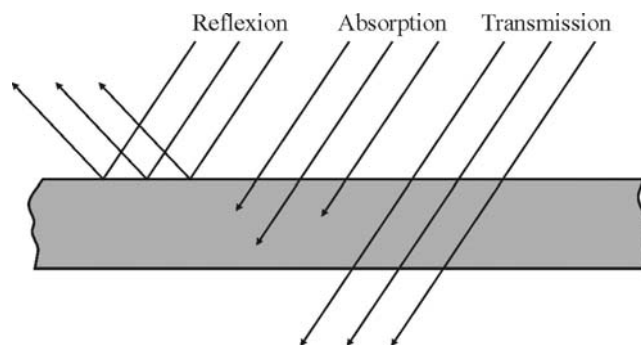


Fig. 1 Energy Transition

$$\lambda_{\max} \cdot T = 2,8979 \cdot 10^{-3} [\text{m K}], \quad (2)$$

λ_{\max} – wavelength of the maximal emission,

T – temperature [K].

The total radiation emission of a black body is described by Boltzmann's Law:

$$E = \sigma \cdot T^4 [\text{W / m}^2], \quad (3)$$

$$\sigma = 5,6697 \cdot 10^{-8} [\text{W / m}^2\text{K}^4].$$

For non-black bodies, the radiation performance is reduced by the emissivity ($\varepsilon < 1$).

$$E = \varepsilon \cdot \sigma \cdot T^4 [\text{W/m}^2]. \quad (4)$$

Under Kirchhoff's conditions, the absorption is equal to the emission of a body. In the same way that all hot bodies emit energy, bodies exposed to radiation absorb energy. The amount of energy absorbed is dependent upon the material's properties. The energy can be either directly reflected (r), absorbed (a) or transmitted through the body (d). Thus, the following applies:

$$r + a + d = 1, \quad (5)$$

r – degree of reflection,

a – degree of absorption,

d – degree of transmission.

This relationship is shown clearly in Fig. 1. For the absorption, equation $a = 1 - e^{-kl}$ applies, with a – absorption coefficient, k – material's constant, and l – material's thickness. For the effective heat transfer between two plates, the following applies:

$$Q_{1,2} = \varepsilon_{1,2} \cdot A \cdot \sigma \cdot (T_1^4 - T_2^4), \quad (6)$$

$Q_{1,2}$ – heat transfer between two surfaces 1,2 ,

$\varepsilon_{1,2}$ – heat transfer coefficient,

A – surface area [m^2],

T – temperature [K],

$\sigma = 5,6697 \cdot 10^{-8} [\text{W/m}^2\text{K}^4]$.

In IR-heating, thermal energy is transmitted in the form of electromagnetic waves. The infrared spectrum lies directly next to the border to the observable light in the wavelength range 0,76...2 μm . The electromagnetic spectrum is shown in Fig. 2.

The infrared spectrum is divided into the short-wave (0,7...2 μm), the medium-wave (2...4 μm) and the longwave ranges (4...1000 μm). The borders are thus somewhat blurred.

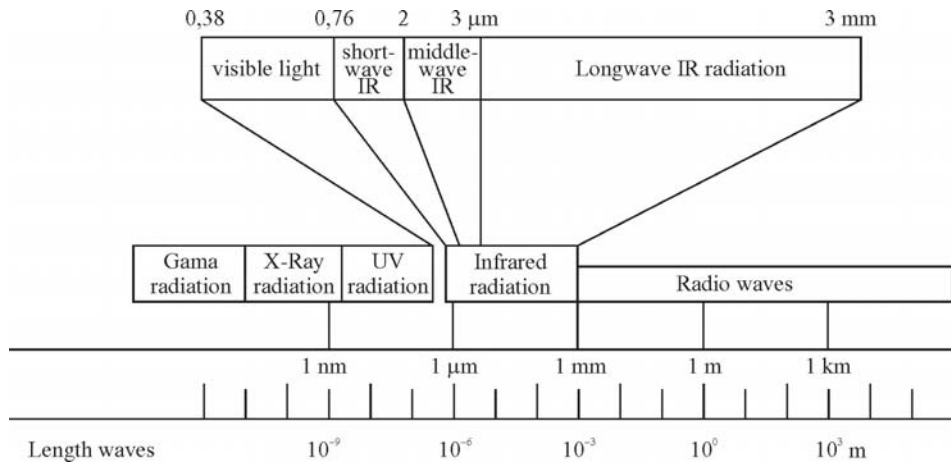


Fig. 2 Electromagnetic Spectrum

All bodies emit IR radiation, depending upon their temperature. High temperatures imply short-wave IR radiation with high intensity. As the temperature decreases, the wavelength increases and the intensity is reduced. The proportional amount that is absorbed by air becomes greater. Tab. 1 shows typical radiation temperatures and their corresponding radiation spectra.

Tab. 1 Typical Radiation Temperatures and Their Corresponding Radiation Spectra

| Radiation Intensity | Unit | Short-wave High | Medium-wave Medium | Long-wave Low |
|---|------------------------|------------------|--------------------|---------------|
| Temperature of the radiation source | K | $3000 \geq 1600$ | 700...1000 | 300...700 |
| Wavelength at peak | μm | $0,8 \leq 1,6$ | 3,0...2,3 | 5,0...3,0 |
| Band of wavelengths | μm | 0,76...2,8 | 5,4...1,4 | 9,2...1,8 |
| Amount of radiation < 2 μm | % | 80...43 | 6...17 | 0...6 |
| Amount of radiation < 4 μm | % | 95...84 | 47...65 | 13...47 |
| Irradiation | kW/m^2 | 1200 40 | 50...20 | 20...10 |
| Degree of efficiency of transition into electrical energy | % | 86...75 | 50...60 | 40...50 |

Using short-wave IR radiation, the highest irradiance and effectivity are achieved. The actual radiation emitters are high-performance halogen bulbs whose emission can be focused on an object using special reflectors. The corresponding heating modules have individually designed cooling ducts that cool not only the connections and wiring, but also the reflectors and quartz glass windows.

The integrated bulbs have an extremely short reaction time (< 2 s), allowing for quick responses to emergency stop situations. Furthermore, preheating of the plant is not necessary. The high radiation intensities make a high heating rate possible while at the same ti-

me minimizing the drying distance (in belt drying processes). Because the radiation can be focused, it is possible not only to create local temperature gradients, but also especially homogeneous heating of large and complicated components.

In contrast to gas heated furnaces, IR technology represents an especially clean method of heating since no exhaust gases, such as NO_x , SO_x or CO_x , are released into the atmosphere. Moreover, samples and components do not receive impurities from the exhaust gases. A complete encasing of the heating system with quartz glass is even possible.

4 MEASURING TECHNOLOGY

It is important that a qualified measuring technique (temperature, expansion, elasticity, moisture, layer thickness) is applicable in order to specifically control the dimensions that are to be set. Three methods for measuring temperature are described in the following, which can be used specifically in combination with short-wave IR heating modules. Since temperature measurements with thermoelements are not possible in transporting steps, only non-contacting (pyrometric) processes will be described here.

The problem here lies in compensating for the multiple reflections of the heating systems, which leads to a supposedly higher component temperature since the additional reflected radiation from the heater onto the surface reaches the pyrometer and is not separated in standard systems.

For measurements of surface temperature of up to ca. 800°C , a precision pyrometer has been developed, having measuring accuracy of $< 1\%$. This pyrometer measures the integral wavelength range of 8...14 mm. In this wavelength range, the quartz glass of the halogen bulb is not transparent, meaning that the multiple reflection effect is inherently suppressed. The pyrometer system is temperature compensated, through which the long term stability of the detectors is additionally increased. Using the integrated optic, a measuring spot adjustment within broad ranges is possible. Direct integration in the heating modules is prepared.

For temperature ranges above 800°C , two different systems were developed. In one of these systems, a special synthetic quartz glass is placed in front of the heating module. This quartz glass has a distinct absorption band at 2,74 mm and blocks the radiation wavelengths coming from the heater. The pyrometer used is exactly set to this wavelength range. Thus, only the resulting radiation from the surface of the object to be measure is recorded and then converted to the surface temperature data using an algorithm. Compensation for emission must then be made using a reference measurement with a thermocouple. Emission changes that occur during the thermal treatment can only be compensated after previous calibration. An alternative pyrometer system is available for temperatures $>800^\circ\text{C}$. This allows for an on-line multiple reflection compensation and an inherent emissivity measurement. This measuring system comprises two separate pyrometers that determine the AC and DC portions of the measuring signal.

Since the heat radiation is brought about by alternating voltage, and the temperature radiation of the surface has no modulation proportion, the emissivity can be determined and the multiple reflection compensated. Kirchhoff's radiation conditions must be given when using this measurement system, however. Additional laser measuring systems were optimized for expansion, elasticity and layer thickness measurements specifically for use

in combination with IR heating modules. This is, however, not a part of this publication and is only mentioned in passing.

5 APPLICATION EXAMPLES

5.1 Drying of Coatings

Because of environmental reasons, the amount of colors, etc. containing solvents has decreased: they have been replaced by water. This has a considerable impact on drying efforts. Standard air drying systems are no longer able to dry or cure these systems using reasonable amounts of energy and space. In contrast to hot air furnaces, short-wave IR heaters are able, depending on the radiation range, to directly initiate the evaporation of the water. Thus, a significantly higher drying rate is achieved. In addition, energy requirements are significantly reduced because less is required to heat the surroundings. With an electrical efficiency of $> 85\%$ and an additional effectivity of ca. 60% thermal energy based on the evaporation of water, 1 kWh is required for the evaporation of 1 kg water in lacquer, etc.

A continual increase in the printing speed as well as significant improvements in quality can only be realized with IR systems.

5.2 Material Processing

An application is presented here in which bundles of carbon fibers are coated in an inert atmosphere. A quadro-elliptic IR furnace was integrated in the processing line. A special quartz glass cylinder, through which the bundles of carbon fibers pass, is integrated in the furnace. Through additional air cooling of the quartz glass cylinder (from outside through the IR heating modules) its temperature can be held to $< 400^\circ\text{C}$ by a C-fiber temperature of ca. 1300°C . Condensation on the quartz glass cylinder is thus avoided. The temperature measurement is made with a special pyrometer system that is focused on the carbon fiber bunches.

The false radiation from the heater is absorbed by the quartz glass cylinder composed of a special glass. The construction principle of this system is shown in Fig. 3.

5.3 Material Testing

IR technology also provides considerable advantages in material testing. The focusing ability of the IR heat radiation is especially noteworthy. By skillfully optimizing the heating system, specific temperature profiles can be set for the components; an application-relevant thermal component stress can be pre-set. Thermal gradients of up to 50 K/cm can be created on large components. Together with thermal radiation densities of up to 1 MW/m^2 and more directed transients of 15 K/s can be set for large components that need to be qualified for extreme thermal shock stresses.

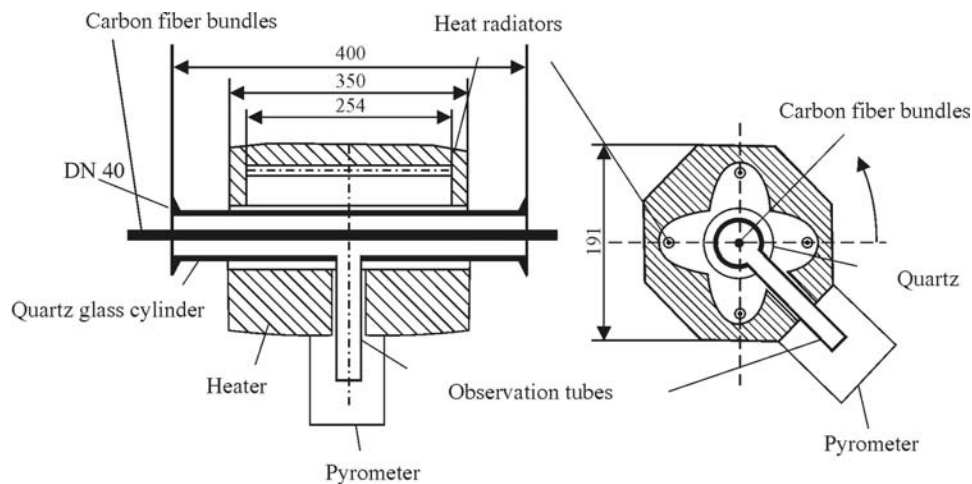


Fig. 3 Layout for Coating C-fibers

6 SUMMARY

Using IR radiation for heating, the following advantages are combined:

- Reduced energy use through higher efficiency (no initial heating times, more directed application)
- Optimized process controlling through faster reaction times and integration of on-line measuring techniques
- Short and precise heating times through extremely high radiation density (1 MW/m^2 , gradients adjustable through multiple heating zones) Low-pollution and clean surrounding conditions due to exhaust-free, high efficiency heating
- Additional energy savings since energy is primarily used only to eliminate solvents and not for heating the components
- Quality production controlled because adapted measuring techniques can be integrated.

In order to realize the optimal degree of efficiency along with optimized quality, however, it is essential that the entire system (heating modules, controlling, measuring techniques) be efficiently and optimally designed.

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INFRACRVENI SISTEMI ZAGREVANJA KOMBINOVANI SA TEHNIKAMA BEZKONTAKTNOG MERENJA

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Ovaj rad opisuje mogućnosti koje su rezultirale iz integracije infracrvenih (IR) sistema zagrevanja u razvoju materijala, u kvalifikacijama koje su pratile ovaj razvoj i obradu materijala. Posebna pažnja je posvećena integralnoj tehnologiji merenja (merenje temperature, širenja i elastičnosti, itd.) kroz koju ovaj proces može biti precizno zabeležen i reprodukovano. U ovom su radu prikazane specifične karakteristike ovog procesa koristeći nekoliko praktičnih primera iz obrade materijala.

Ključne reči: termička merenja, infra crveno zagrevanje, sušenje, procesiranje materijala