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The influence of furnace wall emissivity on steel charge heating

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HIGHLIGHTS

- Spectral emissivity measurement.
- Ceramic fiber insulation mat and high-temperature coatings emissivity.
- Steel charge temperature measurement.
- Influence of furnace wall emissivity on charge heating.

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ABSTRACT

Radiation heat transfer is one of the most important heat transfer modes in high-temperature applications. It is a strongly non-linear process, which depends on the temperature and emissivity of heat exchange surfaces, their geometrical configuration and properties of the surrounding atmosphere. Heat exchange intensity between the surfaces depends mainly on their temperature differences. However, their emissivities influence significantly the radiation heat transfer process as well. Emissivity is a function of surface state or atmospheric chemical reactions, temperature and wavelengths. Because of these non-linearities, it is very complicated to evaluate such a real problem by numerical simulation, and experimental work seems to be the most reliable evaluation procedure. We applied special high-temperature coatings of different emissivities on furnace walls to evaluate the dependence between the furnace wall emissivity and steel charge heating. The emissivity analyses of the coatings used and emissivity measurement results in dependence on wavelength are presented in this paper. The dependence of the charge heating on the furnace wall emissivity, the importance of emissivity wavelength dependence and significant differences of the emissivity effect in electrical and gas heated furnaces are shown. The possible consequences and practical benefits are also discussed in this paper.

1. Introduction

Heat treatment is one of the most used technological operations in practically all kinds of industry. Periodical or continuous type furnaces are often used, for example, in steel and ceramics processing industries, where the processing temperature significantly exceeds 1000 °C [1] in many cases. The charge in a furnace is generally heated by both convection and radiation [2,3] heat transfer mechanisms. However, the radiation heat transfer becomes dominant at high temperatures, independently of the furnace type, which can be gas-fired or electrically heated in most cases.

Radiation heat transfer [2,3] is based on heat energy transfer by electromagnetic phenomena, which happen between surfaces at different temperatures even if no medium is between them. Thus, thermal radiation does not require any medium for the thermal energy transport. However, the medium between the surfaces, for example, the combustion products, can influence the thermal process by radiation energy absorption and it can also emit radiation energy to its surroundings. The radiation heat flux is defined by the radiating surfaces' temperature, their geometrical configuration and their emissivities. Unlike convection and conduction, which are defined by temperature differences, the radiation heat flux is given by the difference of 4th power of temperatures. Hence, the radiation heat transfer takes the dominant role at higher temperatures. The geometrical configuration is defined by the radiation view factor, which describes the space visibility of the radiating surfaces. Finally, the emissivity of the surfaces is the

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radiometric dimensionless quantity which describes their thermal radiation properties.

The surface emissivity ε is one of the most important quantities of the radiation heat transfer process. It is defined as a ratio of the radiation of the surface and black body under the same temperature, geometric, and spectral conditions. The emissivity of real surfaces takes values in the interval from 0 to 1 and is dependent on the material type (metals, plastics, etc.), surface properties (chemical composition, etc.), surface state (roughness, microstructure, etc.), surface (body) temperature [4], and radiation wavelength, direction and polarization grade. The following emissivity definitions, which are described in more detail in [5], are used: spectral directional emissivity, spectral hemispherical emissivity, total directional emissivity, total hemispherical emissivity, band emissivity and effective emissivity. The surface characterization is complemented by additional surface radiative properties: absorptivity, transmissivity and reflectivity. For applications considered in this paper, solid material transmissivity can be omitted; absorptivity according to Kirchhoff's law [6] is equal to the emissivity ε and the reflectivity is $1-\varepsilon$.

If a non-transparent medium appears between the radiating surfaces, for example, combustion products in gas-fired furnaces, it also participates in and influences the heat transfer process. Unlike for solid bodies, the emissivity, absorptivity and also the transmissivity has to be defined for the gas medium in most cases. These quantities are dependent on chemical composition and reactions, wavelength, thermodynamic state of the gas (pressure, temperature) and the mean layer thickness. In the case of burning gas and combustion products, there is typically very strong wavelength dependence, where radiation is emitted and absorbed on specific wavelengths only [6]. A detailed description of radiation heat transfer can be found, for example, in [6–8].

The emissivity is the most important parameter of radiation heat transfer. Knowing it is important for a theoretical analysis of the thermal process as well as for a non-contact temperature measurement. Therefore, a number of emissivity determination methods have been developed. These methods can be used for the emissivity measurement at room temperature [9,10] or at high temperature [10–13]. An overview of different emissivity measurement methods can be found in [14], for example.

The radiation is the dominant process of the heat transfer for a number of high-temperature applications, which often are among high energy-consumption applications as well. Optimization of design and operation of such facilities therefore has significant consequences on their environmental influence and can bring heating process improvements, fuel consumption reductions, and financial savings [15]. The optimization is mostly based on numerical modelling [16,17]. The radiation heat transfer is, however, strongly non-linear and it is quite complicated to build up a full reality-describing model, even if particular emissivity components or other process parameters are known. Simplified models [18] supported by direct measurement [1,5,19] can therefore be very useful for some special purposes and can result in important improvements. However, such simplified models usually cannot provide detailed information leading to full understanding of the thermal process under different conditions.

The radiation process non-linearity is, among other things, also caused by wavelength emissivity dependence, which is very significant for gases [6] and some ceramics materials [11,20] often used in industrial furnaces. It can change the heating process relations, but it cannot be included in numerical simulations using standard numerical software packages. Therefore, we performed a number of experiments using a test-furnace, where we experimentally evaluated the influence of furnace wall emissivity on steel charge heating. High-temperature coatings [21] were used for modification of furnace internal wall emissivity. The emissivity was measured by the direct radiometric method [21] at the required temperature and in dependence on wavelength. Both gas-fired and electric heating systems were used for the experiments. The results of coatings emissivity measurement and charge temperature measurement during heating in the furnace were compared. Significant differences between gas-fired and electric heating systems are discussed in relation to the emissivity wavelength dependence of coatings used. Even if the geometrical configuration in real industrial furnaces can differ, the results show possible approaches to the design optimization of furnaces or heat exchangers by modification of their surface-radiation properties.

2. High-temperature coatings

High-temperature coatings of different emissivity produced by BG SYS HT Ltd (Pardubice, Czech Republic) were applied on the test-furnace internal walls. The coatings are created from an inorganic composite system based on silicon [22] and have been developed for the protection of heat-exposed surfaces. Their specific properties (corrosion and chemical resistance, abrasion resistance, thermal shock resistance, emissivity, etc.) at temperatures up to 1900 °C can be achieved by a suitable combination of individual components of the coatings. They are therefore applied on internal surfaces of high-temperature devices such as industrial furnaces, heat exchangers and combustion chambers to increase their operating life-time and operational efficiency [23,24]. Other research and development work deals with the practical use of such coatings [25,26].

The coatings' main components are binders, fillers and active ingredients. The binders are mixtures of soluble ionic and covalent silica-based cross linkers, colloidal silica and metal-oxide particles. The binder volume fraction varies between 30% and 55% and it influences elasticity, bonding properties, thermal and chemical resistance and the integrity of the coating. Frequently used fillers are TiO_2 or CeO_2; however, the shape and size of the filler particles are more important than their surface chemistry. The fillers are added to the binder in order to improve the physical properties of the coating, for example abrasion resistance, chemical resistance, heat shock resistance, hardness and adhesion. The active ingredients are special types of fillers, which affect particular physical properties of the coating, for example, its thermal or electrical conductivity and optical properties, including emissivity.

We used seven different coatings in our experiments, which consisted of 45–55 vol% of a binder, 9–17 vol% of an active ingredient and the rest a filler. The binder and the filler were the same for all the coatings. Different emissivities of individual coatings were achieved by different active ingredients. The labeling and active ingredients description of the coatings used are in Table 1. Each coating was air-sprayed on the substrates (emissivity analysis samples or removable inside layers of the furnace) and dried at indoor temperature. The coatings' thickness was about 150 μm and their real emissivities in dependence on wavelength were measured by the direct radiometric method. The emissivity measurement procedure is described below and a more detailed description of the coatings can be found in [21] or [22].

Table 1
List of high-temperature coatings used.

Coating label	Active ingredient
S04	Iron powder
S05	Cerium oxide and iron powder
S06	Chromium oxide and iron powder
S09	Magnetite