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Total normal and spectral emittance of refractory materials for high temperature ovens

G. Neuer

Institut für Kernenergetik und Energiesysteme
University of Stuttgart, Postfach 801140
7000 Stuttgart 80, Germany

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ABSTRACT

A measurement device based on the radiation comparison technique is described. It enables us to measure the directional total and spectral emittance between 400°C and 1200°C in the wavelength range 0.5 μm to 8 μm and at angles of up to 72° against the normal to the surface.

Measurements with different types of silica showed that the spectral emittance can be remarkably increased, especially at wavelengths below 5 μm, by adding small amounts of silicon carbide. This is important for the improvement in the efficiency of the heating at different types of furnaces.

INTRODUCTION

Silica stones are commonly used as wall materials at ovens for high temperature processing. One typical example of such ovens are coke ovens possessing large dimensions of 4 to 8 m height and 12 to 18 m depth. The walls are heated by burnt gas within heating flues positioned between the oven chambers. Another example are tank furnaces with arched crown for glass melting by flame heating. In both cases the knowledge of the emittance is important for an optimum design and high emittance values are required to improve the radiation heat exchange. Because the variation of the emittance of oxide ceramics is most pronounced in the wavelength range below 5 μm it is recommended to measure both the total and the wavelength dependent spectral emittance.

MEASUREMENT DEVICE

The emittance measurements are based on the radiation comparison technique. The optical arrangement is shown in Fig. 1. The temperature of the sample (3) is measured within a small radial hole of 1 mm diameter by means of the IKE-LINEARPYROMETER LP2, described by Wörner (1982). A thermoelectric detector (Hilger-Watts-Vacuum thermopile) is mounted inside the vacuum chamber for measurement of the total emittance. For spectral emittance measurements the radiation from the sample surface (3) is directed by a deflection mirror (4) and through a CaF_2-window in the vacuum vessel to the monochromator (8) and to a second thermoelectric detector (9). This part of the optical arrangement enables measurements in the range 1.2 μm to 8 μm. For shorter wavelengths a second mirror (4) is moved into the optical path and a second LINEARPYROMETER (14) is used in combination

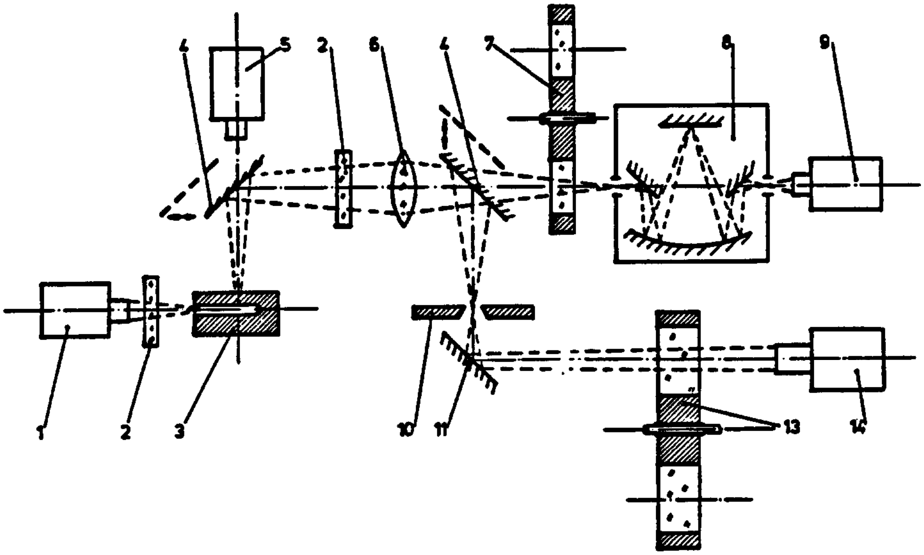

Fig. 1. Schematic diagram of the optical arrangement for the total and spectral emittance measurement

1	LINEARPYROMETER I
2	CaF_2-window
3	sample with radial hole
4	displacable mirror
5	thermoelectric detector I (total emittance)
6	CaF_2-lens
7	wheel with blocking filters
8	monochromator
9	thermoelectric detector I (spectral emittance at 1.2 to 8 μm
10	field stop
11	mirror
13	wheel with interference filters 0.5 to 1.0 μm
14	LINEARPYROMETER II (spectral emittance)

with a wheel for up to 10 interference filters ranging between 0.5 and 1.0 μm. For calibration of the complete optical arrangement the sample is replaced by a heat pipe blackbody described earlier by Neuer et al. (1975). The LINEARPYROMETER (1) measures the cavity temperature whereby an additional mirror is required. But this does not influence the accuracy because the radiation from the blackbody is unpolarized, the LINEARPYROMETER is designed without any polarizing components and the reflectance of the mirror can easily be determined. The complete identity of the arrangement at the calibration and at the measurement is the first presupposition for the application of the radiation comparison method. The second requirement is that the signal of the radiation detectors is proportional to the radiation intensity. Only then is the emittance equal to the ratio of the signal measured at the sample to the signal, measured at the blackbody of the same temperature.

In the case of samples emitting polarized radiation additionally a polarizer has to be placed in the optical path between sample and radiation detector in order to measure both the parallel and the perpendicular polarized contribution. The position of the polarizer has to be identical during calibration and measurement at the sample.

The sample is heated by radiation from a tantalum heating wire. Both sample and heater are assembled in a sample holder which is tiltable in order to be able to measure the angle dependency of the emittance. Because of the ratio of the target diameter to the sample diameter, which is 5 mm to 30 mm, the maximum angle is 75°.

The sample surface is faced by watercooled and blackened sheet metals in order to control the radiation and reflection of surroundings. The measuring chamber can be floated with gas or evacuated up to about 4×10^{-4} Pa.

The surface temperature T_o is determined from the temperature T_B, measured within the radial black body hole by assuming radiation flow from the surface equals heatflow within the sample. The thermal conductivity of the sample has to be known. The evaluation procedure is described earlier by Neuer (1070) and a detailed description of the measurement device is given by Pflugfelder et al. (1990).

The measurement accuracy is influenced by

- keeping constant transmission and reflection properties in the optical path
- stability of the detectors
- accuracy of the temperature measurement

The measurement imprecision resulting from these contributions can be limited below ± 3%.

An essential source of error is the uncertainty of the thermal conductivity which is the determining factor for the calculation of the temperature difference between the radial hole and the surface. Greater temperature differences and accordingly greater temperature errors occur with lower thermal conductivities, higher emittances and temperatures due to increasing heat flux. The spectral emittance values at short wavelengths are considerably more sensitive to temperature errors than those at longer wavelength.

In the case of partly transparent materials, such as oxide ceramics, it has to be taken into account that a thickness which is smaller than the distance between the hole and the surface has to be assumed for the calculation of the temperature difference. Therefore, measurement errors can only be given for specified samples. The inaccuracy of the measurements described in this paper is mainly influenced by transparency of the material and is in range of 10-15%.

Material Description

Different types of silica refractories were tested in order to find out how the radiation properties can be influenced by additives. The application of the material is for coke ovens and therefore high total emittance values are required. The manufacturing process was identical for all investigated materials; they were produced by dry pressing. The individual materials can be described as follows

SiO2-A
This is a normal silica stone of the quality called "dens". Its properties correspond with the german norm DIN1089. The material is bonded on the basis of calcium silicates. The bulk density is 1.85 g/cm^3, the apparent porosity is 20.2% of the volume. The quartz residual is 2.2%.

SiO2-B
The second material differs from SiO2-A essentially by adding 12% SiC to the starting material during production. The resulting density is 1.95 g/cm^3, the apparent porosity 19% vol-% and quartz residual 2%.

SiO2-C
The third type of silica refractory material was produced by mixing the silica with such additives, which form oxides during the production process. The material additionally has a calcium silicate bonding. The bulk density is 1.92 g/m^3, the apparent porosity is 6.0 vol-% and the quartz residual is 0.5%.

The following thermal conductivities given by the manufacturer were used for the calculation of the surface temperatures (values are given in W/m·K)

	SiO2-A	SiO2-B	SiO2-C
1100 K	1.71	2.01	2.01
1300 K	1.96	2.44	2.44
1500 K	2.11	2.60	2.60

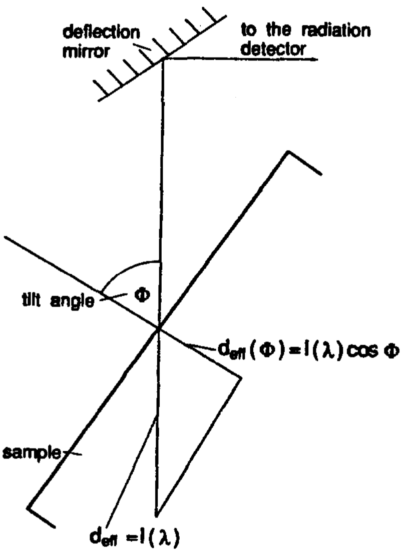

Fig. 2. Determination of the effective radiating layer at semi transparent materials by sample tilting

Transparency investigation

As mentioned above the temperature gradient in the sample perpendicular to the measuring surface leads to measurement uncertainties in the case of materials which are not opaque. The radiation flux cannot be attributed to a surface layer of neglegible thickness with a determined surface temperature, but the emittance has to be defined by the radiation from a layer of finite thickness. This effective layer thickness d_{eff} corresponds to the free path $l(\lambda)$ of the radiation at the wavelength λ. The radiation detector measures the radiation intensities from the entire temperature range between the surface temperature T_0 and the temperature $T_{l(\lambda)}$ at the depth $x = l(\lambda)$.
Because the free path of the investigated materials was not known, a simple method was used to check the transparency:

If we measure the emittance of tilted samples as shown in Fig. 2, the effective layer thickness $d_{eff} = l(\lambda)$ perpendicular to the surface is reduced to $d_{eff}(\phi) = l(\lambda) \cdot \cos\phi$. This is combined with a reduction of the temperature difference within the effective layer, and with increasing tilt angle the measured emittance is approximated to the true emittance of the surface. The influence of angle dependency of the emittance can be neglected in the case of the investigated materials.

Fig. 3 shows the result of such measurements with the material SiO2-A at different tilt angles. For all angles the emittance has been evaluated using the same surface temperature T_0. At 35° the values are only a little lower than at measurement perpendicular to the surface. With increasing angle the emittance decreases and reaches the true values.

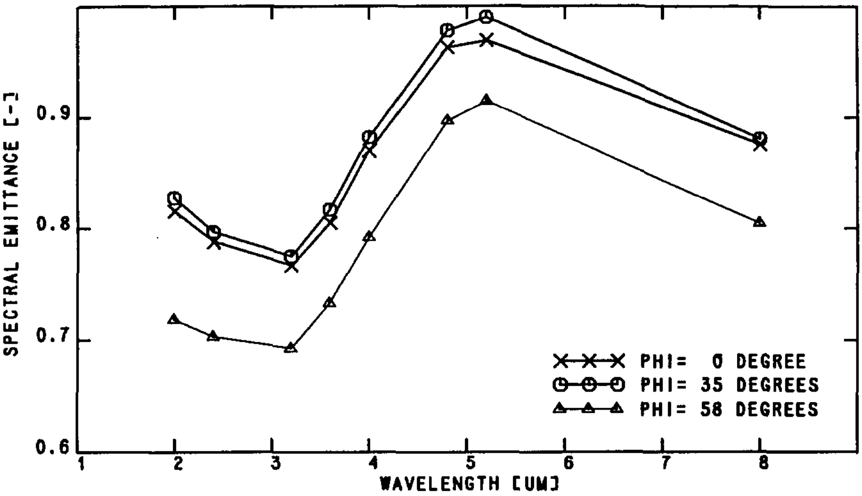

Fig. 3: Spectral emittance of SiO2-A, measured at different tilt angles ϕ of the sample. (surface temperature T_0 = const = 1211 K)

Keeping in mind that, without knowledge of the free path $l(\lambda)$, this is only a qualitative approximation, we can define a reduction of the geometric distance d_0 between the radial hole within which the temperature T_B is measured and the measuring surface. This distance reduction Δd of the different materials was found to be

SiO2-A: Δd = 0.9 mm
SiO2-B: Δd = 0.0 mm (the material is nearly opaque)
SiO2-C: Δd = 1.0 mm

Measurement Results

The total normal emittance results are presented in Table 1 and Fig. 4. In Table 1 both the temperature T_B, measured in the radial hole and the calculated surface temperature T_0 or T_0^* respectively are given. For the calculation of T_0 the geometrical distance d_0 between the blackbody hole axis and the surface is used and for the calculation of T_0^* the distance d_0^*, corrected by Δd as described above has been taken into account. The thermal conductivity values are given above in the section "Sample Description". The spectral emittance values are presented in Table 2 and Fig. 5. The spectral measurement were carried out only at the highest temperature for each material.

TABLE 1

Total normal emittance ϵ_t of different types of silica stones. T_B is the measured blackbody hole temperature, T_o^* is the surface temperature calculated using the corrected distance $d_o^* = d_o - \Delta d$ (in mm)

SiO2-A1 (d_o^* = 1.4-0.9 = 0.5)			SiO2-A2 (d_o^* = 1.4-0.9 = 0.5)					
T_B [K]	T_o^* [K]	ϵ_t [-]	T_B [K]	T_o^* [K]	ϵ_t [-]			
1000	992	0.41						
1003	996	0.40						
1018	1106	0.49	1018	1007	0.62			
1078	1163	0.51	1100	1085	0.62			
1255	1237	0.51	1238	1216	0.66			
			1296	1271	0.67			
SiO2-B1 $d_o^* = d_o$ = 1.5			SiO2-B2 $d_o^* = d_o$ = 1.5			SiO2-C1 d_o^* = 1.5 - 1.0 = 0.5		
T_B [K]	T_o [K]	ϵ_t [-]	T_B [K]	T_o [K]	ϵ_t [-]	T_B [K]	T_o^* [K]	ϵ_t [-]
1012	975	0.77	1003	961	0.84	-	-	-
1040	1002	0.73	-	-	-	-	-	-
1085	1045	0.71	1094	1045	0.82	1042	1032	0.57
1155	1109	0.70	1175	1118	0.80	1115	1104	0.55
1218	1166	0.71	1245	1180	0.79	1199	1185	0.54
1249	1194	0.70	1320	1241	0.82	1255	1240	0.53

TABLE 2

Spectral emittance ϵ_λ of different types of silica stones

λ [μm]	SiO2-A2 T_o^* = 1271 K	SiO2-B2 T_o = 1241 K	SiO2-C1 T_o = 1240 K
2.0	0.65	0.87	0.60
2.4	0.63	0.86	0.60
3.2	0.65	0.85	0.62
3.6	0.70	0.86	0.67
4.0	0.77	0.90	0.76
4.8	0.86	0.97	0.88
5.2	0.87	0.97	0.89
8.0	0.83	0.89	0.88

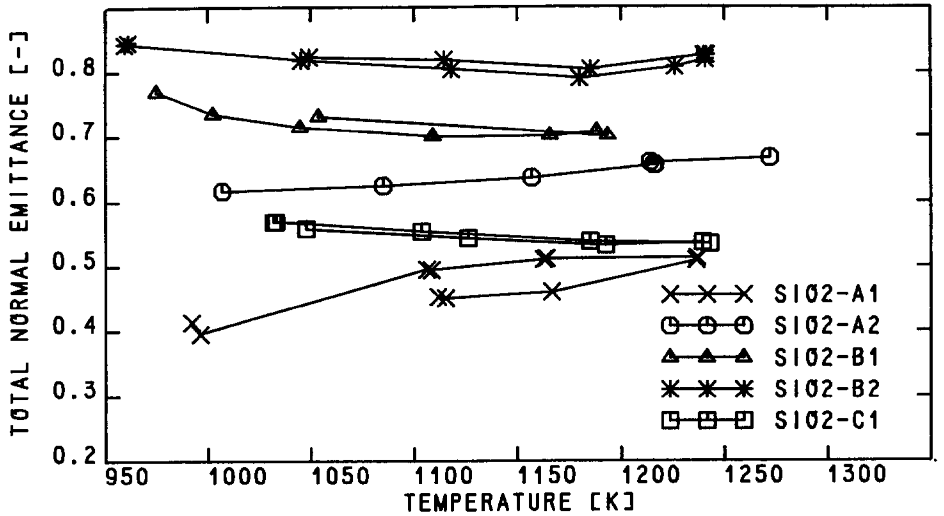

Fig. 4. Total normal emittance of different types of silica stones

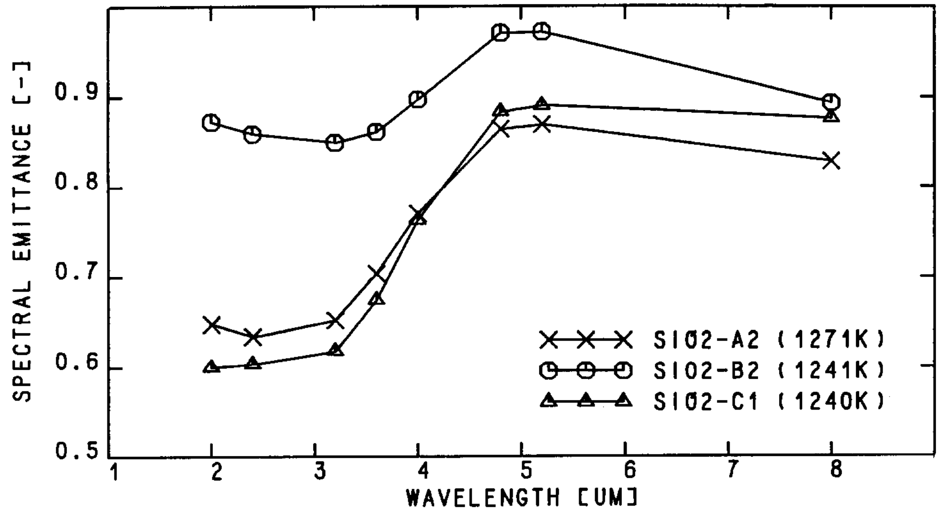

Fig. 5. Spectral emittance of different types of silica stones

DISCUSSION AND CONCLUSIONS

The measurement results clearly show the variation of the emittance with additives to the basic silica material. The variation of the total emittance is mainly caused by a variation of the spectral emittance in the low wavelength range. This is one reason to measure both the total and the spectral emittance. The second reason is

that spectral emittance measurements at different angles give an indication as to the transparency of the material. The carbon content in the material leads to a suppression of the transparency of the silica stones combined with an increase of the total emittance. Additives forming oxides themselves do not have this behaviour and in the observed wavelength range no pronounced variation of the emittance could be observed.

For the practical application of the results the transparency has also to be taken into account if the wall is not isothermal. The effective volume emission related to the surface temperature becomes higher in the case of heating from the rear side and lower if heated at the front face. The thickness of the emitting layer equals to the mean free path which advantageously should be known both for the interpretation of the emittance measurements and for the practical application of the results. Otherwise the results remain more qualitative than quantitative.

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