INSULATING CERAMIC FOAMS FOR HIGH TEMPERATURE FURNACE LINING

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ABSTRACT

The main reasons of applying insulating ceramics as furnace linings are related to energy costs and environmental concerns. From the emission point of view, most industrial furnaces operate in the infrared wavelength range (0.7 to 100 μm) where the thermal transmission by radiation is the major mechanism for the total effective thermal conductivity. This information is fundamental to design the composition and the microstruture of insulating ceramic materials. Commercial Al_2O_3-SiO_2 and Al_2O_3-ZrO_2-SiO_2 linings present high porosity (70 to 85 vol%), but densify during use due to silica based binders. An alternative could rely on plain Al_2O_3 insulating lining, however it presents lower thermal shock resistance and higher thermal conductivity. In this work, alumina-based refractory foams with low thermal conductivity values (0.25 to 1.0 W/mK), high porosity (70 to 84 vol%), good compressive strength and high resistance to thermal shock were applied as insulating lining in furnace operating at 1600°C in air. The performance of the insulating refractory was evaluated considering the energy consumed by the heating elements and the temperature profiles at different points of furnace. Power consumption indicated lower values when using foamed ceramic lining compared to the fiber ones.

INTRODUCTION

The main purpose for using insulating ceramics as furnace lining is due to the energy costs and the environmental concerns. It is well known that thermal insulation capacity depends on engineered designed ceramic microstructures to reduce thermal energy conduction.

Fundamentals concerning thermal-optic properties of ceramic material are essential to point out the optimized pore size range where thermal insulation efficiency can be maximized (1).

The electromagnetic spectrum in Figure 1 highlights that the Infrared (IR) range comprises wavelengths (λ) from 0.7μm to 1000 μm. Because the primary source of infrared is heat or thermal radiation, any matter with a temperature above absolute zero radiates in the infrared range (2). This is caused by the vibration and rotation of atoms and/or molecules. The higher the temperature of an object, the more infrared energy is emitted.

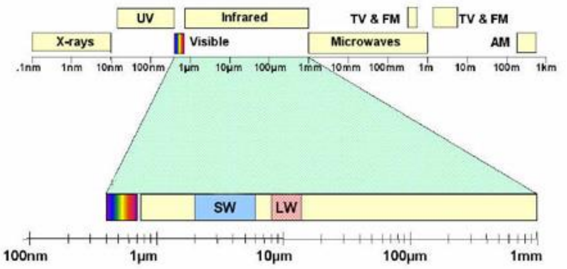

Fig. 1: Electromagnetic spectrum of energy highlighting Infrared radiation, where the shortwave (SW) corresponds to a range of 3-5μm and longwave (LW) to 8-12μm (2).

Considering the Infrared wavelengths, a good thermal insulating material must be able to reduce the intensity of radiation emitted within the temperature range of interest presented in Figure 2. According to the literature (1,3), there are two ways to reach this target: by adding substances which absorb part of the radiation in the wavelength range of interest and/or by introducing micropores to the microstructure to scatter the heat radiation.

However, the effectiveness of each mechanism depends on the wavelength, as most absorbing substances (or opacifiers) do not absorb at lower wavelengths as shown in Figure 3. Therefore, at high temperatures, scattering is the main mechanism to decrease the radiation intensity (1).

Considering the traditional furnace linings, they usually present overall porosity close to 50 Vol-%, which is attractive from the standpoint of mechanical strength, but its high mass is unsuitable regarding energy consumption, weight, ergonomics and thermal shock resistance under relatively fast thermal cycles.

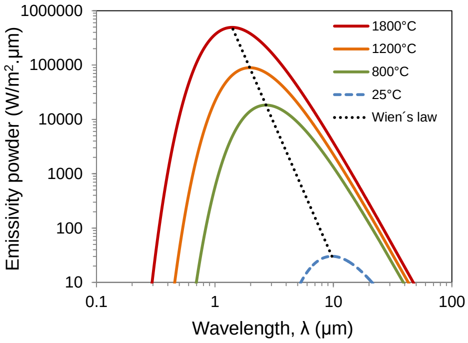

Fig. 2: Emissivity power as a function of wavelength and temperature (3).

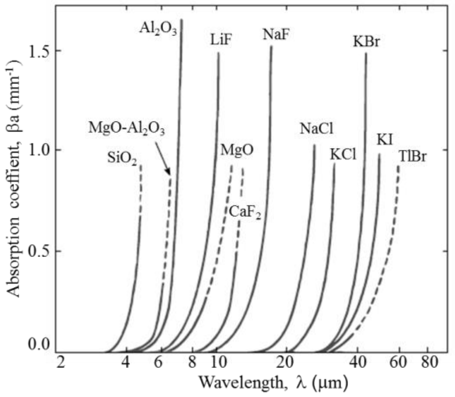

Fig. 3: Absorption coefficient as a function of wavelength for ceramic materials (3).

In addition, these materials have high fused silica content for decreasing thermal expansion, to absorb thermal radiation (4) and enhance thermal shock resistance. However, silica quickly migrates to surfaces under a reducing atmosphere, because solid SiO_2 converts to SiO vapor (4). This may be unacceptable in situations where silica is a contaminant to the product. Furthermore, as mentioned before, SiO_2 does not absorb heat radiation at high temperatures.

Moreover, commercially available Al_2O_3-SiO_2 and Al_2O_3-ZrO_2-SiO_2 linings produced by vacuum forming processes show open porosity in the 70 to 85 vol-% range (5), but they densify during use due to silica based binders. Consequently, heat transfer mechanisms increase and cracks are developed in the whole structure.

An alternative should be plain Al_2O_3 insulating lining, which presents good mechanical strength but shows low thermal shock performance and higher thermal conductivity (4).

Conversely, the characteristics of lower density, high refractoriness, lower thermal conductivity and improved thermal shock resistance of ceramic foams enhance the performance of furnace linings compared to the traditional ones (4,6,7).

In this context, this study evaluates the performance of Al_2O_3-based ceramic foams applied as hot face insulating lining in a furnace operating at 1600°C in air. The ceramic foams present designed microstructure and composition to achieve very low thermal conductivity, high resistance to cyclic thermal shocks and adjusted pore size distribution.

EXPERIMENTAL PROCEDURE

Materials

The green direct-foaming equipment (6) was applied to produce the ceramic foam compositions consisting of >90 wt%Al_2O_3 with two distinct inorganic binders: CAC, Secar 71 from Kerneos, France (4BF Ceramic Foam) and K ino-nanobinder developed at GEMM (ASK Ceramic Foam).

The raw materials used were Al_2O_3 CT3000SG and CL370C, from Almatis, USA, and the additives were Castament FS60, BASF as dispersant, Alpha Olefin Sulfonate as foaming surfactant and Methylcellulose as thickening agent.

Techniques

Firstly, the aqueous and homogeneous mixture of ceramic powders and additives was poured into the direct-foaming equipment container. The designed device has two compressed air controls. One (P = 2 kgf/cm^2) is used to pump the suspension from the container through a rubber pipe to the **T** point, where compressed air (P = 4 kgf/cm^2) is injected into the suspension. As a result, a high volume of small and homogeneous air bubbles is generated and the foamed mixture can be cast into the mould.

The foamed suspensions were cast into plates (300 mm x 300 mm × 50 mm). The plate´s curing of composition containing CAC was carried out at 50°C in a climatic chamber (Model VC 2020, Vötsch) under controlled humidity (~80%) for 24 h. The foam plate containing K ino-nanobinder was cured at 50°C without humidity control.

Afterwards, the demoulded samples were dried at 110°C for 24h and sintered at 1600°C for 5 h.

The thermal conductivity up to 1250°C was determined by the parallel hot wire method (TCT 426 Netzsch) .The characterization of the morphology, pore structures and porosity of the ceramic foams were carried out using X ray micro tomography (μCT, Skyscan 1172) with a resolution of 7μm/pixel and scanning electron microscopy (SEM, Inspect S50 Leica).

The performance of ceramic foams as hot face insulating lining was evaluated considering the consumed energy by the heating elements and the temperature profiles at different points of furnace, as schematically shown in Figure 4.

Data of temperature, current, voltage and power were carried out by equipment SENSOFT, specially developed for this project. In Figure 5 it is shown the Lindberg furnace and the equipment for recording the data.

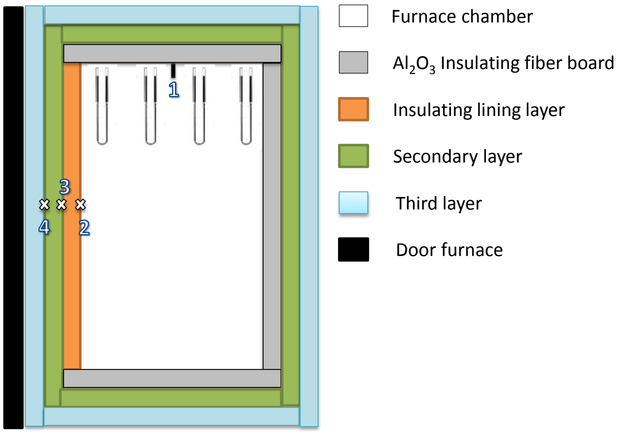

Fig. 4: Scheme of the cross section of furnace chamber showing the heating elements, the lining layers and thermocouples 1, 2, 3, 4 for temperature measurements.

Fig. 5: Lindberg Furnace connected to equipment for recording data of temperature, current, voltage and power at heating up to 1600°C.

RESULTS AND DISCUSSION

This section is organized as follows. Firstly, the effect of direct-foaming equipment on the morphological, physical, and thermal properties of Al_2O_3-based foam is presented. Then, the temperature profiles and power supply data of the heating elements are presented.

Effect of foaming process on morphological, physical and thermal properties

Macroscopically ceramic foams present two levels of pore sizes; the small ones surrounded by solid particles at the pore walls, whereas the big ones or cells are scattered in the microstructure.

Ideally, the small pores should be eliminated to result in denser struts and, consequently, improved mechanical strength.

Considering these aspects and optimizing the particles packing of the ceramic compositions, foamed microstructures with denser pore walls were feasible using the direct-foaming equipment, as shown in Figure 5.

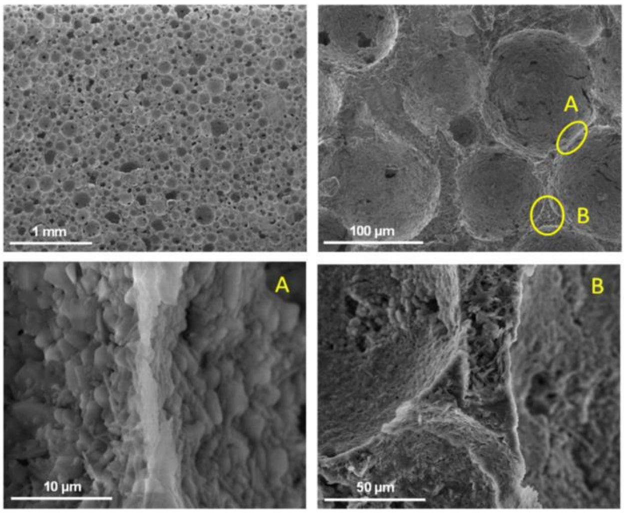

Fig. 5: SEM micrographs of the high Al_2O_3 foam microstructure after sintering at 1500°C for 5h. A and B regions show good packing of particles at the solid struts.

Figure 6 highlights the significant differences in the porosity and pore distribution of Al_2O_3-based foams prepared via traditional stirring or with the direct-foaming equipment.

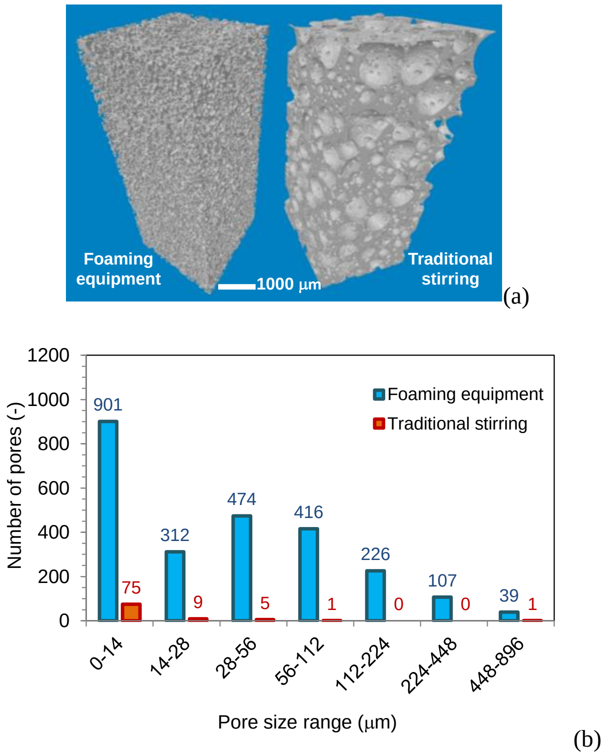

Fig. 6: µCT images of Al_2O_3 foams after sintering at 1500°C for 5h produced by (a) foaming equipment (P: 76 v%) or traditional stirring (P: 60 v%) and, (b) the volumetric pore size distribution for both processing routes.

According to Pelissari et al [10] there is a narrow optimum range of pore diameters where the effective thermal conductivity is minimized at high temperatures. Acording to them, the existence of the optimum pore diameter range is due to the radiation interaction with the microstructure. Figure 7 shows the effective thermal conductivity versus pore diameter for Al_2O_3 foam with 86.6 vol % of porosity at 1500 °C obtained from FEM Model 2, which is quite similar to a microstructure of ceramic foams of this work.

Based on that, considering the high number of pores in the range 0-14µm (Fig. 6b) and also the properties presented in Table 1, the ceramic foams compositions produced in this work most probably present high performance as insulating at high temperatures.

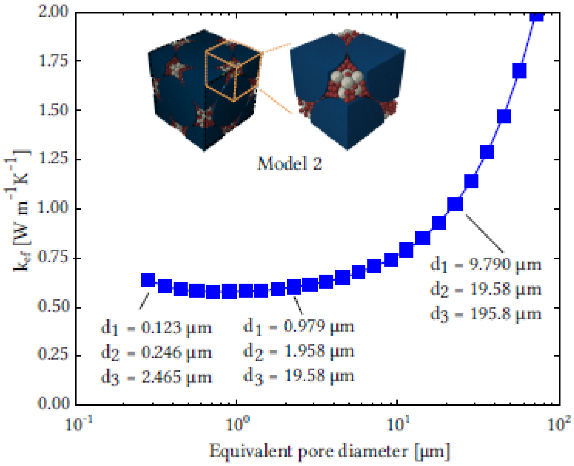

Figure 7: Effective thermal conductivity for Al_2O_3 foam with with 86.6 vol % of closed porosity at 1500 °C – FEM Model 2 results. The diameters d_1, d_2 and d_3 refer to the three pore sizes. (10)

Tab. 1: Properties of ceramic foams fired at 1600°C for 5h.

Foam Ceramic	Bulk density, ρ (g/cm^3)	Relative density, $\rho_{relative}$ (-)	Total porosity, P_t (%)	Thermal conductivity at 1200°C, k_t (W/mK)
ASK	0.84 ± 0.02	0.24 ± 0.01	76.00 ± 1.50	0.36
4BF	0.66 ± 0.01	0.18 ± 0.01	84.61 ± 0.10	0.25

Energy consumption and temperature profiles of the ceramic foam insulating lining

The ceramic foams from Table 1 were applied as the hot face insulating lining in furnace, as schematically shown in Fig. 4. Then, the performances of these foams were compared to the Al_2O_3 insulating fiber board used as standard hot face linings in furnace.

The insulating fiber board presents density of 0.51g/cm^3, open porosity of 84% and thermal stability up to 1830°C.

Figure 8 and 9 show the temperature profiles and power data of the furnace as a function time for Al_2O_3 insulating fiber board and 4BF foam ceramic, respectively.

Figure 10 shows the differences of temperature profiles at the cold face (thermocouple 3) for the materials used as insulating lining layer. And Figure 11 highlights that the ceramic foams presents temperature profiles shifted to lower values in comparison to the Al_2O_3 insulating fiber.

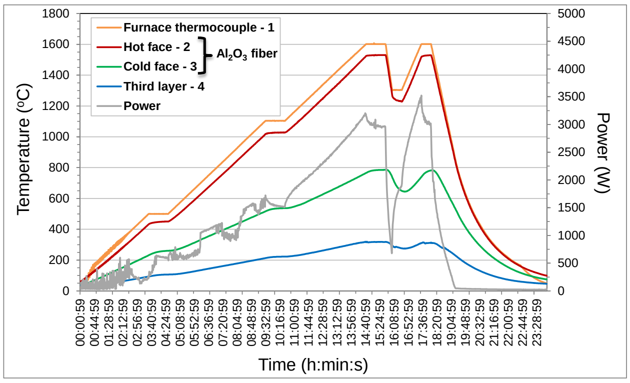

Fig. 8: Temperature profiles and power as a function of time for the Al_2O_3 insulating fiber lining.

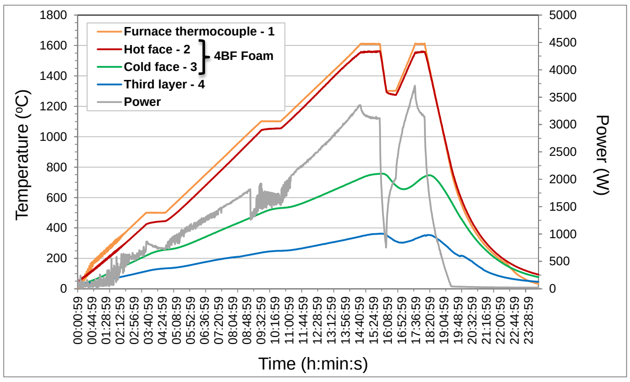

Fig. 9: Temperature profiles and power as a function of time for the 4BF ceramic foam lining.

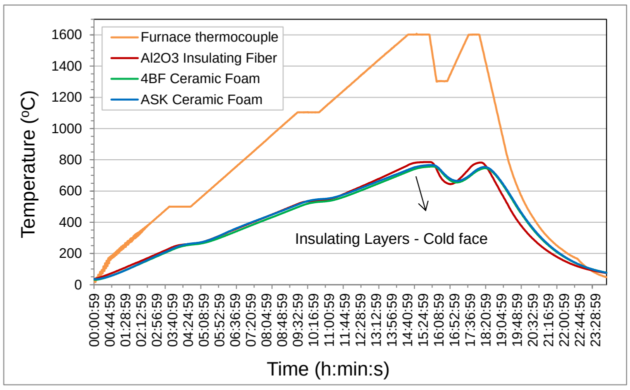

Fig. 10: Temperature profiles at the cold face (thermocouple 3) for different insulating lining materials.

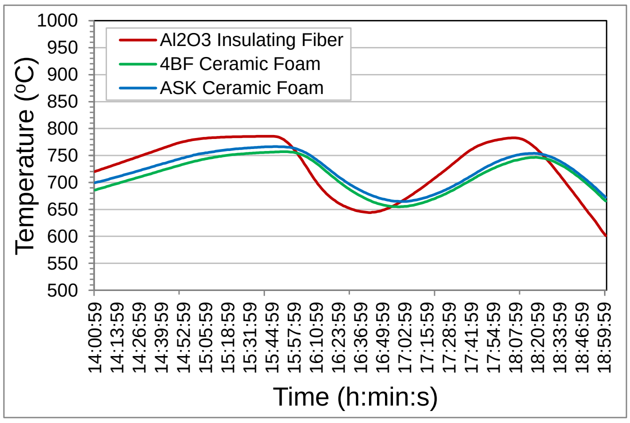

Fig. 11: Temperature profiles at the cold face for different insulating lining materials.

However, power data did not allowed a clear association between insulating materials properties and energy consumption by heating elements. Probably this is due to the small contribution of a single insulating plate in the total energy calculation. Further research on this topic needs to be undertaken in order to consider the contribution of all surfaces of the furnace chamber in the energy consumption.

CONCLUSION

This study has shown the key importance of insulating materials properties in the energy consumption of a furnace operating at 1600°C. The results show that due to their properties, such as high porosity level, adequate pore size distribution, low and stable values of thermal conductivity, the 4BF and ASK ceramic foams performed very well as the hot face insulating lining in furnace at 1600°C in air. Both ceramic foams presented temperature profiles shifted to lower values in comparison to the Al_2O_3 insulating fiber lining.

ACKNOWLEGMENTS

The authors are grateful to HOREF (312RT0453) de CYTED for supporting this work.

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