Designing Insulating Ceramic Foams for High-Temperature Furnace Lining*

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The main reasons for using insulating ceramics as furnace linings are due to saving energy costs and environmental concerns. Traditional materials have high fused silica content to lower thermal expansion, absorb thermal radiation and enhance thermal shock resistance. However, silica migrates to surfaces under a reducing atmosphere, because solid SiO_2 converts to SiO vapour. Commercial Al_2O_3–SiO_2 and Al_2O_3–ZrO_2–SiO_2 linings present high porosity (70–85 vol.-%), but densify during use due to silica based binders. An alternative should be a plain Al_2O_3 insulating lining, but it presents low thermal shock performance and higher thermal conductivity. This work presents the design and application of Al_2O_3-based foamed lining refractories with low and stable thermal conductivity (0,25 W/m·K), high porosity (84 vol.-%), good compressive strength and high resistance to thermal shock. This material was applied as insulating lining in a glass melting furnace operating at 1700 °C. The proposed porous ceramic showed lower energy consumption when compared to commercial ones.

1 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 optimised pore size range where thermal insulation efficiency can be maximized [1].

The electromagnetic spectrum in Fig. 1 highlights that the Infrared (IR) range comprises wavelengths (λ) from 0,7–1000 µm.

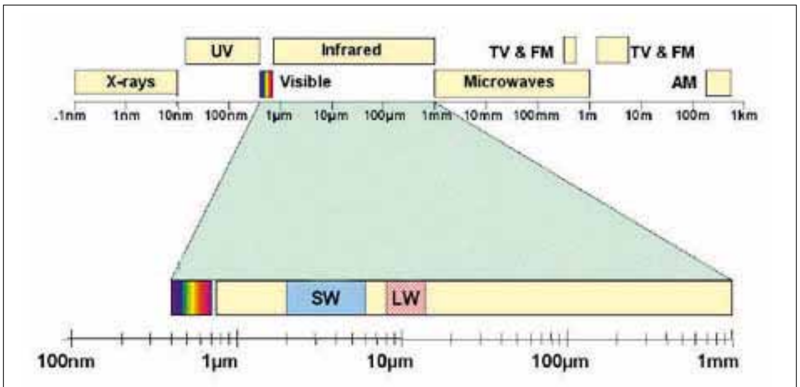

Fig. 1 **Electromagnetic spectrum of energy highlighting infrared radiation, where the shortwave (SW) corresponds to a range of 3–5 µm and longwave (LW) to 8–12 µm [2]**

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. 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 Fig. 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

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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 Fig. 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.

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 vapour [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 porosity in the 70–85 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 foam applied as insulating lining in a glass-melting furnace which operates at 1700 °C. The ceramic foam presents designed microstructure and composition to achieve very low thermal conductivity, high resistance to cyclic thermal shocks and adjusted pore size distribution.

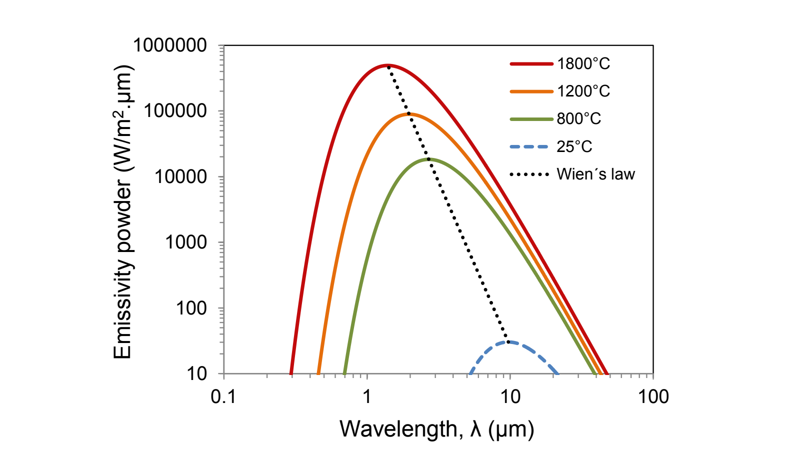

Fig. 2 Emissivity power as a function of wavelength and temperature [3]

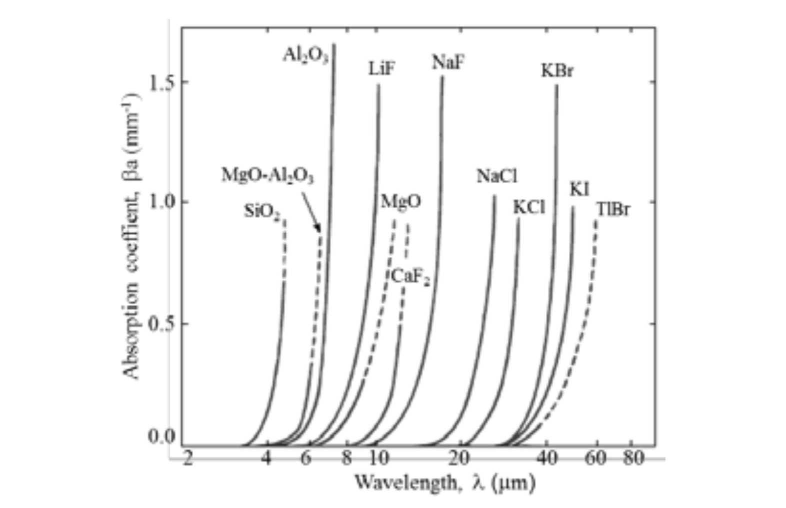

Fig. 3 Absorption coefficient as a function of wavelength for ceramic materials [3]

2 Experimental procedure

2.1 Materials

The green direct-foaming equipment developed by Salvini et al. [6] was applied to produce the ceramic foam composition consisting of 93 mass-% Al_2O_3 – 7 mass-% CaO.

Aqueous alumina suspensions containing 53 vol.-% of solids (Al_2O_3, CT3000 SG and CL370C, Almatis/US), dispersant (Castament FS60, BASF/DE), foaming surfactant (Rheocell-Rheofill, BASF/DE), thickening agent (Methocell 306, Dow Chemical/US) and hydraulic binder (CAC, Secar 71, Kerneos/FR) were prepared in a high shear mixer. Additional Al_2O_3-based compositions, such as high alumina (>98 mass-% Al_2O_3) and alumina-mullite (75 mass-% Al_2O_3 and 25 mass-% $3Al_2O_3 \cdot 2SiO_2$) were also prepared in order to highlight the versatility of the direct-foaming equipment and process.

2.2. 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/cm²) is used to pump the suspension from the container through a rubber pipe to the T point, where compressed air ($P = 4$ kgf/cm²) 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 × 300 mm × 40 mm), cylindrical (40 mm × 40 mm) and prismatic

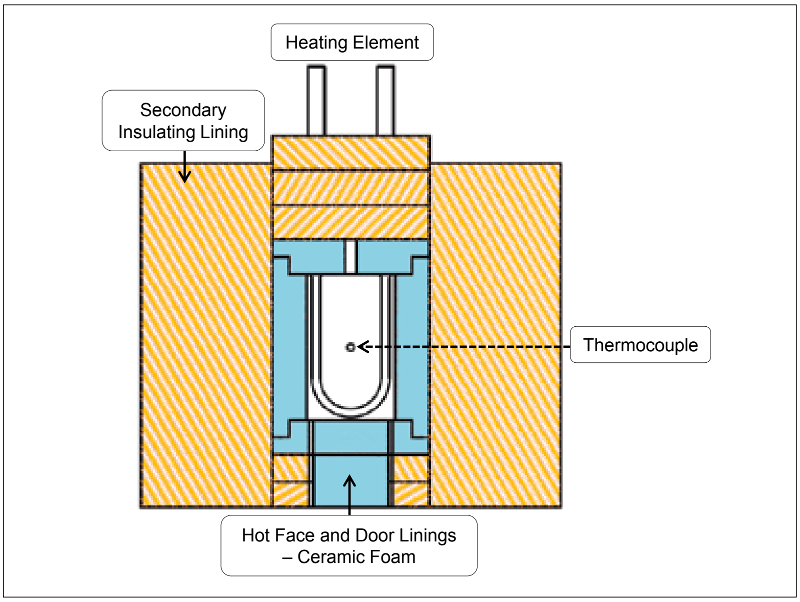

Fig. 4 Schematic drawing of the glass melting furnace for 1700 °C

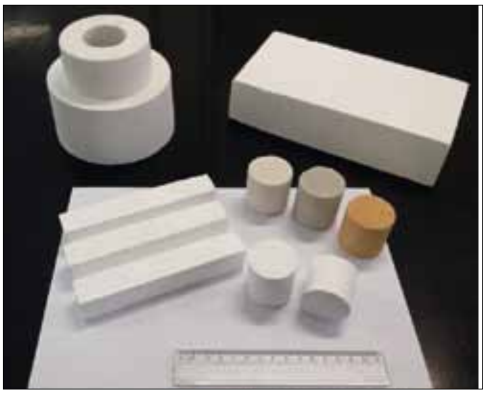

Fig. 5 Al_2O_3-based foam pieces produced by direct-foaming equipment [6]

samples (220 mm × 110 mm × 65 mm). The plates' curing step was carried out at 50 °C in a climatic chamber (Model VC 2020, Vötsch/DE) under controlled humidity (~80 %) for 24 h. These conditions favour the formation of the most stable cement hydrates, which improve the mechanical behaviour of the materials. Afterwards, the demoulded samples were dried at 110 °C for 24 h and sintered at 1500 °C for 5 h.

The splitting tensile strength was determined according to the ASTM C496/C496M-11 and the thermal conductivity up to 1250 °C was determined by the parallel hot wire method (TCT 426 Netzsch/DE). The characterization of the morphology, pore structures and porosity of the macro-porous alumina were carried out using X ray micro tomography (µCT, Skyscan 1172) with a resolution of 7 µm/pixel and scanning electron microscopy (SEM, Inspect S50 Leica).

The sintered plates of ceramic foam were cut and placed as the hot face and door insulating linings in a 1700 °C glass melting furnace, as schematically shown in blue in Fig. 4. The secondary insulating lining consisted of a ceramic fiber blanket (Fiberfrax 1200).

The performance of ceramic foam as insulating lining was evaluated considering the consumed energy by the heating elements and the cycled thermal shock resistance.

Concerning energy consumption, the current (I, Ampere) and voltage (V, Volt) applied to the heating elements ($MoSi_2$ Kanthal) were recorded as a function of temperature (T, °C). Then, power (W, J/s) was calculated by current × voltage expression.

Similar tests were also carried out when a commercial insulating refractory was used as the hot face and door linings. The commercial product consists of 62 mass-% Al_2O_3, 34 mass-% SiO_2 and 1,4 mass-% Fe_2O_3, has a porosity of 55 vol.-% and thermal conductivity at 400 °C of 0,41 W/m·k.

Regarding thermal shock tests, the furnace door lined with ceramic foam was closed and heated up to 1700 °C. Then, the vertical lift door was lowered so that the ceramic foam lining was exposed to room temperature for 30 s. After that, the lift door was moved upward and the furnace was closed. The thermal shock tests of the ceramic foam door lining lasted 10 cycles. After that, the material of the door lining was visually evaluated in order to observe any developing cracking.

3 Results and discussion

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

3.1. Effect of the foaming process on morphological, physical, mechanical and thermal properties

A clear benefit of the direct-foaming equipment in the fabrication of foamed ceramics is its feasibility of producing samples with large dimensions and different geometry, as shown in Fig. 5.

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 optimising the particles packing of the ceramic compositions, foamed microstructures with denser pore walls were produced by the direct-foaming equipment. Using compressed air allowed for a more effective particle rearrangement decreasing the large pores at the cell walls. Fig. 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.

Tab. 1 shows the results of different Al_2O_3-based foams produced by the direct-foaming equipment. Considering the porosity level of the evaluated Al_2O_3-based foams, the attained mechanical strength values are remarkably higher than data from the literature (0,3–1,7 MPa for bulk density varying from 0,5–1,0 g/cm³) [8, 9]. These results strengthen the benefits associated to the ceramic processing factors, such as dispersion and particle packing of the suspensions and using the foaming equipment.

3.2. Energy consumption and thermal shock performance of the ceramic foam insulating lining

Due to its interesting properties shown in Tab. 1, the ceramic foam in the Al_2O_3–CaO system was applied as the hot face and door insulating linings in a glass-melting furnace for 1700 °C.

Fig. 7 shows the power supply data of the furnace heating elements as a function of temperature for the two insulating materials considered (ceramic foam and a commercial insulating refractory).

Regarding the commercial insulating material, it is important to mention that the power data was collected up to 1300 °C only. After that, the dotted line indicates a possible trend of the results.

It can be observed at temperatures higher than 700 °C that the heating elements required more power to achieve the temperature set point when the commercial material is used as hot face insulating lining. This could be attributed to its properties (porosity of 55 vol.-% and thermal conductivity 0,41 W/m·K) and also to the ceramic system (62 mass-% Al_2O_3, 34 mass-% SiO_2 and 1,4 mass-% Fe_2O_3), which are not effective for absorbing and/or scattering the thermal radiation at high temperatures (Fig. 2–3).

According to the literature [2, 3], thermal transmission by radiation is a major contribution to the total effective thermal conductivity at high temperatures. Obviously, this information is fundamental for the microstructure design of insulating ceramic materials.

Power data supply of insulating ceramic foam indicated this material consumed around 6 % less energy at 1300 °C in comparison to the commercial one. The data behaviour suggests the well-known link between energy consumption by the heating elements and the properties of the considered insulating materials. In case of the ceramic foam, the lower power supplied at 1300 °C may be explained by the low thermal conductivity associated to high porosity volume of the foam material in comparison to the commercial one.

In addition, it can be seen that the atmosphere of the furnace chamber also has important implications concerning energy consumption by the heating elements. When tests were carried out under vacuum (10–12 bar), the power supply data for the

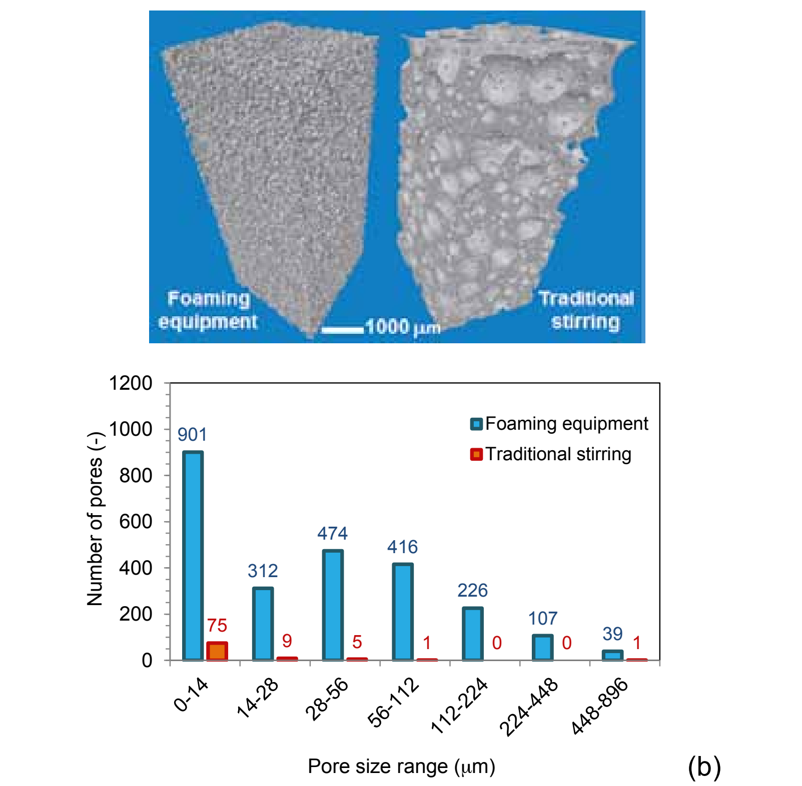

Fig. 6 a–b µCT images of Al_2O_3 foams after sintering at 1500 °C for 5 h produced by (a) foaming equipment (P: 76 vol.-%) or traditional stirring (P: 60 vol.-%), and (b) the volumetric pore size distribution for both processing routes

Tab. 1 Properties of macroporous ceramic compositions fired at 1500 °C for 5 h

Ceramic System	Bulk Density ρ [g/cm³]	Relative Density $\rho_{relative}$ [–]	Total Porosity P_t [%]	Flexural Strength σ_f [Mpa]	Thermal Conductivity at 1200 °C k_t [W/m·K]
Al_2O_3	0,95 ± 0,06	0,24 ± 0,01	76,01 ± 1,44	15,23 ± 1,55	0,86
Al_2O_3-Mullite	0,87 ± 0,04	0,23 ± 0,01	78,14 ± 0,99	8,34 ± 1,08	0,72
Al_2O_3-CaO	0,66 ± 0,01	0,18 ± 0,01	84,61 ± 0,10	3,20 ± 0,35	0,25

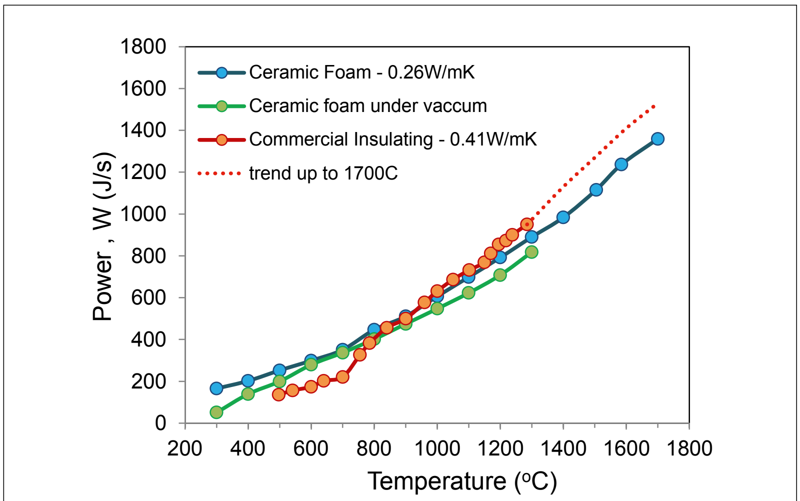

Fig. 7 Power supplied to the heating elements as a function of temperature for two types of insulating material lining

Fig. 8 **Foamed ceramic samples after 10 cycles of thermal shock testing at 1700 °C in air**

ceramic foam indicated an even lower energy consumption (close to 16 % at 1300 °C) in comparison to commercial material, because the heat radiation is reduced in a vacuum.

However, further research on this topic needs to be undertaken before the association between materials properties and energy consumption is clearly understood for different ceramic systems.

The cyclic thermal shock tests were recorded on video, which was shown at the ALAFAR 2016 presentation. Fig. 8 depicts the images of foamed ceramic samples without cracking or spalling after 10 cycles of thermal shock testing, indicating that the foamed material performed very well at the severe thermal shock conditions.

4 Conclusions

This study has shown the key importance of insulating materials properties in the energy consumption of a glass melting furnace operating at 1700 °C.

The results show that due to its properties, such as high porosity, low and stable values of thermal conductivity, high resistance to cyclic thermal shock and good mechanical properties, the ceramic foam in the Al_2O_3–CaO system performed very well as insulating lining in a furnace.

The results showed that the insulating ceramic foam material consumed around 6 % less energy at 1300 °C in comparison to a commercial one. Furthermore, the consumption could be even reduced to 16 % under vacuum.

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