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Processing and thermoluminescent response of porous biomorphic dysprosium doped yttrium disilicate burner

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HIGHLIGHTS

- Bio-prototyping of yttrium disilicate burner is reported.
- The effect of Dy^{3+} on thermoluminescent response of yttrium disilicate is discussed.
- Radiant efficiency of the biomorphic yttrium disilicate burner is evaluated.

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ABSTRACT

The present study reports a process to develop a porous biomorphic dysprosium doped yttrium disilicate burner from biotemplating of Luffa Cylindrica and its thermoluminescent response is evaluated. Processing parameters such as rheological behavior of the ceramic suspensions, surface chemistry of the nanoparticles, microstructure, thermal stability of the biotemplating, as well as thermoluminescent response of the nanoparticles, were investigated. Ceramic suspensions prepared at pH 10 from tetramethylammonium hydroxide, 2 wt% polyacrylic ammonium salt and 0.4 wt% carboxymethylcellulose exhibited shear thinning behavior, suitable apparent viscosity for replica method and porous microstructure as sintered. Promising thermoluminescent result of the yttrium disilicate nanoparticles was observed at 580 nm and at 180 °C. The burner prototype sintered at 1500 °C for 7 h exhibited reticulated shape similar to biotemplating, porous microstructure with mean grain size around 1 μm, no apparent cracks, pycnometric density of 3.21 g cm^{-3} (80% of theoretical density; 4.04 g cm^{-3}) and radiant efficiency of 13%. These results show that controlling stability of nano particles leads to form a microstructure with controlled grain size and porous distribution, which enhances porous burner efficiency.

1. Introduction

The transition from fossil to green economy (low-carbon energy system) depends on innovative processes to generate, share and save energy. According to the International Energy Agency (IEA) to provide universal access to energy by modern energy technologies is one of the greatest challenges of this century [1,2].

Based on the context of green economy [3–8] porous ceramic burners have been shown as a sustainable technology to produce heat and lighting even though by burning low calorific fuels from modern biomass, such as ethanol and biogas [9,10]. Basically the combustion process in a porous ceramic burner consists in heat circulation. The heat comes from the gas to the ceramic solid and it comes from the ceramic solid to the gas [11]. Good review works on porous burners are available in elsewhere [12–16].

With intrinsic proprieties as high thermal stability, high hardness, low density and chemical inertness, ceramic materials such as alumina (Al_2O_3) [17], silicon carbide (SiC) [18], yttria stabilized zirconia (YSZ) [19] have been shown as interesting materials for gas burner applications. Yttrium disilicate ($Y_2Si_2O_7$) exhibits melting point of 1775 °C, stability in oxidant environment and significant optical and mechanical properties [20–22]. Despite of having many advantages, $Y_2Si_2O_7$ has five polymorphs (y, $\alpha \xrightarrow{1225^{\circ}C} \beta \xrightarrow{1445C} \gamma \xrightarrow{1535^{\circ}C} \delta$) [23–26] and the stabilization of each phase has not been consolidated yet. Hence, most of contributions have been aimed on synthesis of $Y_2Si_2O_7$ powders by sol-gel [27], hydrothermal [28] and solid-state reaction [29]. Therefore, many issues on processing of $Y_2Si_2O_7$ have to be investigated.

Colloidal processing is a method to form reliable ceramic components whereby the structure of ceramic suspension is controlled

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for a desired shape forming. This method is accomplished by a high temperature heat treatment for consolidation of the particles to be satisfied [30–32]. In recent work, Santos et al. [33], developed β-$Y_2Si_2O_7$ reticulated ceramics from biotemplating of the vegetable sponge gourd of Luffa Cylindrica. The sponge architecture is interesting for gas burner design because its reticulated structure can improve gas burning and light emission.

Rare earth doped yttrium disilicate ($Y_2Si_2O_7$:RE) exhibits promising luminescent response. Diaz et al. [34] prepared β-$Y_2Si_2O_7$:Dy^{3+} nanoparticles, which light emission was 40% of the Y_2O_3:Eu^{3+}. GONZALÉZ et al. [35] observed white, red and green light emission from $Y_2Si_2O_7$:Ce^{3+},Tb^{3+}; $Y_2Si_2O_7$:Eu^{3+} and $Y_2Si_2O_7$:Tb^{3+} respectively. Considering the experience from our previous work on colloidal processing of β-$Y_2Si_2O_7$ [33] and bio-prototyping [36], the present study aims to obtain dysprosium doped yttrium disilicate porous burner prototype from bio-templating of Luffa Cylindrica. The effects of particle size-shape, viscosity of suspension, bio-template architecture and thermal treatment on the formation a porous microstructure of the burner prototype are reported. In addition, thermoluminescent response and radiation efficiency of the burner prototype are evaluated.

2. Experimental

By hydrothermal method [33] β-$Y_{1.95}Dy_{0.05}Si_2O_7$ powders with pycnometric density (ρ) of 4.04 g cm^{-3} and specific surface area (SSA) of 10.9 m^2 g^{-1} were produced.

The mean particle size (d_{50}) was measured by means of Photon Correlation Spectroscopy (PCS, ZetaPALS Analyzer, Brookhaven Instruments). For PCS measurements an aqueous suspension with 0.01 vol% solids at pH 10, which is a good condition to disperse particles [33], was prepared. For dispersion of particles tetraethylammonium hydroxide (TMAH, Sigma-Aldrich) was used as deflocculant. The homogenization of ceramic suspensions was performed on a ball mill for 24 h.

Zeta potential (ζ) in aqueous medium was evaluated with a light scattering analyzer (ZetaPALS, Brookhaven Instruments Corporation). Stock suspensions with 0.5 g L^{-1} solids were prepared with NaCl 10^{-3} M as an indifferent electrolyte. HCl and KOH solutions were used to set the pH of the stock suspensions from acid to alkaline condition (pH 5.6–12). Further, 0–3 wt% of polyacrylic ammonium acid (PAA, Duramax D3005) was added to the stock solution. All suspensions were homogenized in an ultrasound cleaner for 2 min (Dr.Hielscher 400US).

The stabilization parameters for yttrium disilicate suspensions are from our previous work [33]. Therefore, β-$Y_{1.95}Dy_{0.05}Si_2O_7$ suspensions with 25 vol% were prepared with tetramethylammonium hydroxide (TMAH, Sigma-Aldrich), 1 wt% PAA, 0.4 wt% CMC (carboxymethyl-cellulose, Sigma-Aldrich). All suspensions were homogenized in a ball mill for 24 h, using alumina spheres ($Ø_{spheres}$ = 10 mm).

The flow behavior of β-$Y_{1.95}Dy_{0.05}Si_2O_7$ suspensions was evaluated with a rheometer (Haake RS600, Thermo Scientific). The sensor system consisted of a double-cone rotor and a stationary plate (DC60/1°). The flow behavior of the suspensions was characterized in the control rate mode (CR) and compared with rheological models available in rheometer database (Haake Rheowin Data Manager v. 3.61.0.1). All measurements were evaluated at 25 °C by increasing the shear rate ($\dot{\gamma}$) from 0 to 1000 s^{-1} in 5 min, holding for 2 min at 1000 s^{-1} and returning to 0 s^{-1} in 5 min. For each CR step 200 points were measured.

The sponge gourd (Luffa Cylindrica, LCy) was used as a template. LCy was cut and shaped like a bulb lamp (40 × 40 × 10 mm). Immersion of samples was performed in β-$Y_{1.95}Dy_{0.05}Si_2O_7$ suspension for 30 min (optimized time) [37]. After the excess ceramic material had been squeezed out, the samples were dried at environmental temperature for 24 h. The impregnated samples were sintered in a vertical furnace (Lindberg/Blue M), where the thermal treatment conditions were based on thermal and gravimetric analysis (TGA/TDA) results of LCy fibers. The microstructure of the sintered samples was evaluated with scanning electron microscopy (MEV, TM3000 Hitachi and MEV, INCAx-act Oxford Instruments).

The performance of the ceramic burner prototype was evaluated by means of the radiant efficiency (N_{rad}), which consists in the ration between the chemical energy from the fuel and thermal energy from the porous structure (Equation (1)) [38]. For gas burning test methane (CH_4, 99.5%, 150 kgf cm^{-2}, ΔH_L = 6.200 Kcal kg^{-1}, White Martins, Brazil) and butane (C_2H_{10}, 99.5%, 2.2 kgf cm^{-2}, ΔH_L = 11.900 Kcal kg^{-1}, White Martins, Brazil) gases were used as fuels. To measure the burner temperature during operation an optical pyrometer (Minipa, MP 350, T_{max} = 700 °C, Δ_T = ±2 °C) was used. The basic set-up performed to measure Nrad is illustrated in Fig. 1.

$$\mathbf{Nrad} = \left(\frac{Qrad}{v_g.\Delta H_L}\right) \times 100\ [\%] \quad (1)$$

where,

- Qrad = τ. T^4 [W m^{-2}];
- τ = 5.6697.10^{-8} W m^{-2} K^{-4} (Boltzmann constant);
- T = Temperature [K];
- V_g = fuel flow [cm^3 min^{-1}];
- ΔH_L = calorific fuel power [kcal kg^{-1}];

Thermoluminescence (TL) measurement of β-$Y_{1.95}Dy_{0.05}Si_2O_7$ particles was performed on a thermoluminescence reader (Risø TL/OSL-DA-20) based on a heating condition up to 700 °C and a spectrometer (Ocean Optics, model QE65 Pro) with spectral sensibility from 200 to 950 nm. The samples were heated at a heating rate of 2 °C s^{-1} up to 400 °C in nitrogen atmosphere. Before TL measurements, samples were irradiated with γ dose 2 kGy using ^{60}Co.

3. Results and discussion

Fig. 2a shows the mean particle size distribution of $Y_{1.95}Dy_{0.05}Si_2O_7$ particles measured by PCS. As a result, β-$Y_{1.95}Dy_{0.05}Si_2O_7$ particles exhibited a narrow particle distribution with mean diameter (d_{50}) of 242 nm, whereas the theoretical diameter (d_{BET}) was 35.7 nm. This significant size difference was

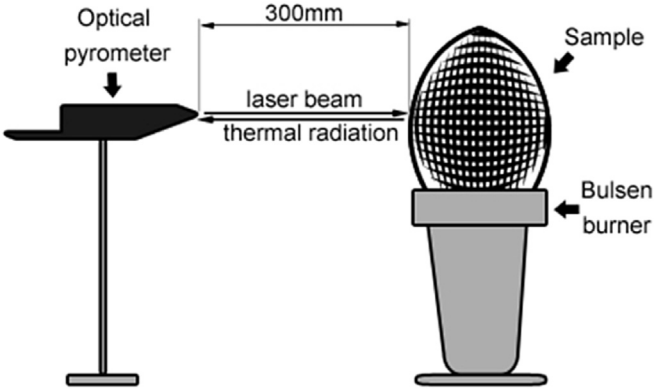

Fig. 1. Basic diagram of set-up performed to evaluate radiant efficiency of β-$Y_{1.95}Dy_{0.05}Si_2O_7$ burner prototype.