Robust Joule-heating ceramic reactors for catalytic CO oxidation

Fangsheng LIU\textsuperscript{a}, Zhibo ZHAO\textsuperscript{a}, Yuyao MA\textsuperscript{a}, Yi GAO\textsuperscript{a}, Jiajie LI\textsuperscript{a}, Xun HU\textsuperscript{a}, Zhengmao YE\textsuperscript{a}, Yihan LING\textsuperscript{b,*}, Dehua DONG\textsuperscript{a,*}

\textsuperscript{a}School of Materials Science and Engineering, University of Jinan, Jinan 250022, China
\textsuperscript{b}School of Materials and Physics, China University of Mining and Technology, Xuzhou 221116, China

Received: August 23, 2021; Revised: April 12, 2022; Accepted: April 22, 2022
© The Author(s) 2022.

Abstract: Joule-heating reactors have the higher energy efficiency and product selectivity compared with the reactors based on radiative heating. Current Joule-heating reactors are constructed with electrically-conductive metals or carbon materials, and therefore suffer from stability issue due to the presence of corrosive or oxidizing gases during high-temperature reactions. In this study, chemically-stable and electrically-conductive (La\textsubscript{0.80}Sr\textsubscript{0.20})\textsubscript{0.95}FeO\textsubscript{3} (LSF)/Gd\textsubscript{0.1}Ce\textsubscript{0.9}O\textsubscript{2} (GDC) ceramics have been used to construct Joule-heating reactors for the first time. Taking the advantage of the resistance decrease of the ceramic reactors with temperature increase, the ceramic reactors heated under current control mode achieved the automatic adjustment of heating to stabilize reactor temperatures. In addition, the electrical resistance of LSF/GDC reactors can be tuned by the content of the high-conductive LSF in composite ceramics and ceramic density via sintering temperature, which offers flexibility to control reactor temperatures. The ceramic reactors with dendritic channels (less than 100 µm in diameter) showed the catalytic activity for CO oxidation, which was further improved by coating efficient MnO\textsubscript{2} nanocatalyst on reactor channel wall. The Joule-heating ceramic reactors achieved complete CO oxidation at a low temperature of 165 °C. Therefore, robust ceramic reactors have successfully demonstrated effective Joule heating for CO oxidation, which are potentially applied in other high-temperature catalytic reactions.

Keywords: Joule heating; ceramic reactor; microchannel reactor; temperature control; CO oxidation

1 Introduction

Many catalytic reactions are conducted at high temperatures to accelerate reaction kinetics, and even heat input is required to meet the enthalpy demand of reactions, such as endothermal dry and steam reforming of methane. Accordingly, heating reactor plays an important role in achieving fast reaction rates and high energy efficiencies. Conventional reactors are based on radiative heating by electrical furnaces in laboratories or through fuel combustion in industries [1], and include heat transfer process and complicate system with large volumes, leading to large temperature gradient within reactors [2,3]. It needs to be maintained at high temperatures while reactors only occupy a small volume ratio in the system [4,5], which greatly reduces system energy efficiency. Some studies have demonstrated Joule-heating reactors constructed by electrically-conductive catalysts or catalyst supports [6]. When current passes through...
the reactors, heat is generated to warm catalysts directly [7]. Compared with the indirect radiative heating, the Joule heating can achieve the higher energy efficiencies owing to the reduced reactor sizes (potentially reduced to 100 times smaller than conventional reactors) and the elimination of heat transfer process [8]. Reactions occur on the hot surface of catalysts [9]. As a result, side reactions within conventional reactors can be avoided in Joule-heating reactors because high-temperature region is limited near catalyst surface. Therefore, high product selectivity can be achieved over Joule-heating reactors.

Currently, there are two types of Joule-heating reactors: metal-based reactors and carbon-based reactors [10–12]. Catalytic metal foam or mesh was used to build reactors to investigate reaction mechanism or perform reactions [13,14]. Resistive FeCrAl alloy was coated with a catalytic layer for dry and steam reforming of methane and the removal of CO and toluene in air [3,8,15]. Electrically-conductive carbon-based materials were employed as catalyst supports, which was heated up by current to reach reaction temperatures. Carbon cloth-supported MnO2 catalyst for formaldehyde removal was regenerated by Joule heating [16]. Qiao et al. [2] fabricated graphene oxide reactor using 3D printing, and it can reach temperature up to ~3000 K at a ramp rate of ~10^4 K·s^{-1} for synthesizing Ru nanoparticles supported on carbon. Both types of Joule-heating reactors have limitations in practical applications. Metals are readily oxidized by oxidant gases or corroded by acidic gases during high-temperature reactions. Additionally, metal reactors provide limited active surface. Carbon-based reactors can provide high surface area while the reactors cannot be used in the presence of oxidants due to the risk of carbon oxidation. Therefore, chemically-stable materials are highly desired for building Joule-heating reactors.

Ceramics are well-known for high chemical stability at high temperatures and widely used as catalyst supports or reactors, such as honeycomb ceramics and ceramic microchannel reactors [17,18]. Some functional ceramics have certain electrical conductivity. For example, perovskite ceramics have been employed as the electrodes of solid oxide cells utilizing their electrical conductivity and catalytic activity, which are operated at 600–800 °C [19,20]. CeO2-based fluorite ceramics have low electrical conductivity, and show good chemical compatibility with perovskite ceramics, which provides the possibility to tune the electrical conductivity of perovskite/fluorite composite ceramics [21]. In addition, the internal surface of ceramic reactors can be varied through ceramic fabrication processes. This study, for the first time, proposed robust ceramic reactors based on Joule heating.

Our group has developed ZrO2 microchannel reactors with channel sizes less than 100 µm, which were fabricated by a mesh-assisted phase-inversion process [22]. In this study, the process was used to prepare (La0.80Sr0.20)0.95FeO3 (LSF)/Gd0.1Ce0.9O2 (GDC) microchannel reactors with LSF as an electrically-conductive phase [23], and the electrical resistance of the ceramic reactors was tuned by LSF/GDC ratio as well as sintering temperature, so that the heating ramp can be controlled to reach the destination temperature of the ceramic reactors. LSF/GDC microchannel reactors based on Joule heating demonstrated high catalytic performance for CO oxidation, which requests quick response in the treatment of automobile exhaust.

2 Materials and methods

2.1 Fabrication of ceramic membrane reactors

Microchannelled ceramic membranes were prepared by phase-inversion and subsequent sintering processes [24], as reported in our previous study [25]. Firstly, polyethersulfone (PESF, Radel-300) was dissolved in N-methyl-2-pyrrolidone (NMP, 99%, Shanghai Macklin Biochemical, China) with a weight ratio of 15%. Then, 57.8 g of LSF (Fuelcell Materials, USA) and GDC (Fuelcell Materials, USA) powders were dispersed in 23.4 g of the above solution, and 0.43 g of polyvinylpyrrolidone (PVP, M_w = 40,000, Shanghai Macklin Biochemical, China) was added as a dispersant. The homogenous slurry was formed after ball-milling for 48 h with a planetary ball mill machine (Kejing, China). The LSF contents in LSF/GDC mixture were set as 20, 30, and 40 wt%. The slurry was degassed by a vacuum pump before casting into a stainless steel mould, and then coagulant (water) was applied on the top of slurry to conduct phase-inversion for 1 h. Ceramic green bodies were dried overnight in an oven set as 55 °C. Ceramic membrane reactors with a thickness of about 1 mm and a diameter of about 10 mm were formed after sintering at 1200, 1250, and 1300 °C. Silver past was painted on two sides of the ceramic membrane, and silver wires with a diameter of 0.3 mm were attached to the two sides. After sintering at 350 °C for 30 min, porous silver layers on both sides were formed to collect current.

www.springer.com/journal/40145
2. 2 Catalyst coating and characterization

To improve the catalytic activity of the ceramic reactors for CO oxidation, MnO$_2$ catalytic washcoat was deposited on channel wall surface by an impregnation process [26–28]. 1.42 g of MnC$_4$H$_6$O$_4$·4H$_2$O (> 99%, AR, Shanghai Macklin Biochemical Co., Ltd., China) was dissolved in 8.58 g of deionized water by magnetic stirring. The catalyst precursor solution was filled into the channels of the ceramic membranes, and the excessive solution was blown off by compressed air. The catalyst precursor was turned into a nanocatalyst layer after calcination at 500 °C for 2 h. The microstructure of ceramic reactors and catalyst layer was observed with a scanning electron microscope (SEM; Phenom, ProX, the Netherlands). The porosity and pore size distribution of ceramic reactors were measured by a mercury intrusion porosimeter (AutoPore IV 9500, Micrometrics).

2. 3 Catalytic performance test

The ceramic reactors were fixed on one end of an alumina tube by ceramabond (552-VFG, Aremco Products Inc., USA), and a K-type thermocouple touched the reactor surface to monitor reactor temperature on gas-feeding side. The alumina tube with the reactor was inserted into a large alumina tube with one end closed to collect effluent gas. The assembled device was wrapped with insulation wool to reduce heat loss. Silver wires were connected to a direct current (DC) power supply device (PLD-6005, NanJing HuiHeng Scientific Instrument Co., Ltd., China), and current was applied on the ceramic membrane to heat the reactors. As shown in Fig. 1, a gas mixture of 1 vol% CO, 20 vol% O$_2$, and 79 vol% Ar was fed into the channelled reactor at a flow rate of 50 mL/min to conduct CO oxidation, and then the effluent gas mixture was analyzed by the gas chromatograph (GC, GC-2014, Shimadzu, Japan). CO conversion was calculated according to Eq. (1):

\[
\text{CO conversion} = \frac{\text{CO}_{\text{in}} - \text{CO}_{\text{out}}}{\text{CO}_{\text{in}}} \tag{1}
\]

3 Results and discussion

3. 1 Controlling reactor temperature

Reactors are required to maintain at a certain temperature to accelerate and stabilize reactions. The temperature of the reactor heated by furnaces is normally controlled by a PID controller through comparing the reactor temperature and setting temperature. Power is applied on heating elements when the reactor temperature is lower than the setting temperature, until reaching the setting temperature. The communication issue between thermal couple and the PID controller can cause overheating. In contrast, the temperature of the reactor based on Joule heating is controlled directly by applied current or potential according to Joule’s Law:

\[
Q = \frac{U^2}{R} - I^2Rt \tag{2}
\]

As the ohmic resistance of perovskite ceramics used in this study decreases with temperature, two control modes would perform differently. Under current control, heat generation decreases with the increase of reactor temperature so that reactor can be stable at a certain temperature, which is determined by the applied current. Figure 2(a) shows that the reactor was heated at different currents, and the reactor temperature was rapidly increased initially and stabilized at different temperatures, which increases with the applied current. It took only 5 min to reach 83.7, 108.7, 135.2, and 201.2 °C at the applied currents of 0.5, 1.0, 1.5, and 2.0 A, respectively. Moreover, the current control can automatically adjust heating to prevent overheating and cooling reactor due to external interferences, such as suddenly changing gas flow rate. As gas was added without pre-heating, gas took heat away when passing through reactors. Therefore, gas flow affected the reactor temperature. As shown in Fig. 2(b), without feeding gas, the reactor heated at 1.0 A showed a temperature about 113.4 °C. Introducing Ar at a flow rate of 50 mL/min caused the sudden decrease of reactor temperature, which consequently increased reactor resistance. According to Joule’s Law, the increased
amount of heat was generated, resulting in the increase of reactor temperature. Then, the reactor temperature stabilized at 114.7 °C. The reactor temperature can also be automatically adjusted to about 115.1 °C after further increasing gas flow rate to 100 and 200 mL/min subsequently. When the gas flow rate was decreased back to 50 mL/min, the reactor temperature was decreased to the initial temperature of 114.7 °C. Overall, the reactor temperature stabilized at a small range of 113.4–115.1 °C at gas flow rates from 0 to 200 mL/min, which confirms that the reactor temperature is under current control. Therefore, the current control mode not only readily controls reactor temperature but also automatically adjusts reactor temperature in the case of external interferences.

However, potential control mode causes the continuous heating or cooling. As shown in Fig. 3, the reactor heated at 1.0 A showed stable temperature, and the reactor temperature was drastically increased when switching to potential control mode at 1.8 V. The temperature increase caused the increase of current due to the decreased reactor resistance, reaching to a device limit of 5.5 A. Then, the reactor was switched to current control mode at 1.0 A, and the reactor temperature was stabilized within about 150 s. When the reactor heating was switched to potential control mode at 1.7 V, the reactor temperature was continuously decreased within 800 s. Under the potential control, the reactors are continuously heated or cooled according to Joule’s Law and the change of ceramic resistance with temperature. In contrast, current control mode enables automatically adjusting heating to stabilize reactor temperature. Therefore, the ceramic reactor based on Joule heating can precisely control the reactor temperature under current control.

3.2 Effect of ceramic composition

Joule’s Law shows that reactor resistance greatly affects heat generation, which offers a flexible way to control the reactor temperature by tuning reactor resistance. In this study, ceramic reactors were made with two types of ceramics: high-conductive LSF and low-conductive GDC with electrical conductivities of ~100 and $1.0 \times 10^{-5}$ S/cm [29,30], respectively. Accordingly, reactor resistance can be tuned through varying LSF contents in the composite ceramics. The LSF contents were set as 20, 30, and 40 wt%. The SEM images of the ceramic reactors sintered at 1250 °C are shown in Fig. 4. The ceramic reactors have a dendritic channel structure, with channels (less than 100 µm) gradually splitting into small channels from one side to the other side of the ceramic membranes [22]. As the LSF content was increased, channel wall became dense because LSF has the higher sinterability than GDC. The porous structure
also affects the electrical conductivity of ceramic reactors as electrons transfer faster in the denser structure.

As shown in Fig. 5, the LSF content greatly affects the reactor temperature via reactor resistance, which is calculated according to Ohm’s Law. The reactor temperature increases with the applied current while at different rates. The reactor with 20 wt% LSF shows the fastest increasing rate due to the highest resistance, and it is because the reactor with the lowest LSF content shows the least dense structure of channel wall. The reactor was heated up to 250 °C, which reached the maximum power output (300 W) of the DC power supply device. Figure 5(b) shows that reactor resistance decreases with temperature, which has more influence on the ceramic reactor with the less LSF content. As the reactor temperature was increased, the temperature showed less influence on reactor resistance.

3.3 Effect of sintering temperature

The above study mentioned that ceramic wall density potentially affects reactor resistance, and the wall density can be readily tuned by sintering temperature [31]. Accordingly, ceramic reactor resistance can be adjusted by sintering temperature. As sintering temperature was increased, channel wall became dense while channel structure was retained, as shown in Fig. 6.

As shown in Fig. 7, the reactor sintered at 1200 °C could not be heated up from room temperature due to large resistance (~400 Ω), which results in small

---

Fig. 4 Cross-sectional SEM images of ceramic reactors and channel wall with different LSF contents: (a, d) 20 wt%, (b, e) 30 wt%, and (c, f) 40 wt%.

Fig. 5 (a) Reactor temperature changing with applied current and (b) reactor resistance changing with reactor temperature at different LSF contents.
Fig. 6  Effect of sintering temperature on the microstructures of the reactor with the LSF content of 20 wt%: (a, d) 1200 °C, (b, e) 1250 °C, and (c, f) 1300 °C. (a–c) Reactor channel structure and (d–f) channel wall structure.

Fig. 7  (a) Reactor temperature changing with the applied current and (b) ceramic reactor resistance changing with the reactor temperature at different reactor sintering temperatures.

currents generated within the potential limit (64 V) of the power supply device. Reactor resistance was reduced by heating the reactor with an electrical furnace to 290 °C. Then, current could heat up the reactor. The reactors sintered at 1250 and 1300 °C could be heated up from room temperature (18 °C) by applying current, and the reactor sintered at 1250 °C was heated up more rapidly because of the higher resistance. Therefore, the resistance of ceramic reactor can be adjusted through sintering temperature so as to tune the Joule heating.

3. 4 Catalytic reaction performance

According to the above studies, ceramic reactors with 20 wt% LSF sintered at 1250 °C were employed to perform CO oxidation. The ceramic reactor with a porosity of 49.4% shows two ranges of pore size: large channels of about 100 µm and small pores (about 0.2 µm) within channel wall, as shown in Fig. 8. Although perovskite LSF and fluorite GDC demonstrated certain catalytic activity during reaction, MnO\textsubscript{2} nanocatalyst was coated over channel wall by an impregnation process to improve the catalytic performance. Catalyst coating was optimized through repeating the impregnation process. As shown in Fig. 9, repeating impregnation deposited more MnO\textsubscript{2} catalyst particles, and formed uniform nanoparticle coating after infiltration for 3 times. Further coating caused catalyst coating cracking due to particle aggregation.

www.springer.com/journal/40145
The catalytic performance of the Joule-heating reactors was tested in CO oxidation, and the effect of MnO₂ catalyst on CO oxidation is shown in Fig. 10. As LSF/GDC ceramic has catalytic activity owing to oxygen storage and electrical conductivity, the reactor without catalyst coating demonstrated the complete CO oxidation at 260 °C. After coating MnO₂ catalyst over reactor channel wall for one time, the reactor showed no improvement in the catalytic performance due to the small amount of catalyst and the intrinsic catalytic activity of the composite ceramic. Repeating the coating process for 2 and 3 times reduced the temperature of complete CO oxidation to 210 and 165 °C, respectively. Further repeating the coating process has no effect on the catalytic performance according to the comparison of the reactors with catalyst coating for 3 and 4 times. It is because the coating process caused catalyst aggregation, as discussed above. Therefore, with suitable catalyst coating over the ceramic reactor wall, the ceramic reactor based on Joule heating can substantially reduce the temperature of CO oxidation. The durability of CO oxidation reaction over the reactor was conducted at 180 °C under Joule heating for 50 h. As shown in Fig. 10(b), CO conversion decreased initially and became stable at the end of the test.

### 4 Conclusions

This study has successfully demonstrated robust ceramic reactors based on Joule heating, which are chemically stable at high reaction temperatures in contrast to metal- and carbon-based reactors. Ceramic reactor resistance decreases with temperature, and hence the ceramic reactors under current control can automatically adjust...
heating to prevent overheating or cooling reactors according to Joule’s Law. The ceramic reactors were made from high-conductive LSF and low-conductive GDC so that reactor resistance can be readily adjusted by the weight ratio of LSF and GDC as well as ceramic density via sintering temperature. The ceramic reactors prepared by phase-inversion process have dendritic channel structures with channel sizes less than 100 µm, which enables coating catalyst to improve the catalytic performance though ceramic reactors itself have certain catalytic activity for CO oxidation. The ceramic reactors based on Joule heating showed a low complete CO oxidation temperature of 165 °C. Therefore, the robust ceramic reactors based on Joule heating are promising for conducting high-temperature catalytic reactions with high energy efficiencies.

Acknowledgements

Prof. Dehua DONG acknowledges the financial support by the National Natural Science Foundation of China (15132123) and Jinan Science and Technology Bureau (2020GXRC033).

References

[1] Herrera L, Hogg D, Cooper J, et al. Reducing the water usage of post-combustion capture systems: The role of water condensation/evaporation in rotary regenerative gas/steam heat exchangers. Appl Energy 2019, 239: 434–453.
[2] Qiao Y, Yao YG, Liu Y, et al. Thermal shock synthesis of nanocatalyst by 3D-printed miniaturized reactors. Small 2020, 16: 2000509.
[3] Li JJ, Lu XF, Wu F, et al. Metallic-substrate-supported manganese oxide as Joule-heat-ignition catalytic reactor for removal of carbon monoxide and toluene in air. Chem Eng J 2017, 328: 1058–1065.
[4] Kumar A, Baldea M, Edgar TF. A physics-based model for industrial steam-methane reformer optimization with non-uniform temperature field. Comput Chem Eng 2017, 105: 224–236.
[5] Latham DA, McAuley KB, Peppley BA, et al. Mathematical modeling of an industrial steam-methane reformer for on-line deployment. Fuel Process Technol 2011, 92: 1574–1586.
[6] Silva VLM, Santos LMINBF, Silva AMS. Ohmic heating: An emerging concept in organic synthesis. Chem A Eur J 2017, 23: 7853–7865.
[7] Lu YR, Nikritjuk P. A fixed-bed reactor for energy storage in chemicals (E2C): Proof of concept. Appl Energy 2018, 228: 593–607.
[8] Wismann ST, Engbaek JS, Vedelbo SB, et al. Electrified methane reforming: A compact approach to greener industrial hydrogen production. Science 2019, 364: 756–759.
[9] Nie ZF, Hou YQ, Deng JS, et al. The combined effect of heat transfer and skin effect on Joule heating for silicon rod in Siemens reactor. Appl Therm Eng 2017, 125: 856–869.
[10] Colina-Ruiz RA, Hoy-Benítez JA, Mustre de León J, et al. Cu2ZnSnS4 thin films prepared with a Joule-heated graphite closed-space sulfurization system. Appl Phys A 2019, 125: 299.
[11] Li JJ, Lu XF, Wu F, et al. Electroplated palladium catalysts on FeCr alloy for Joule-heat-ignited catalytic elimination of ethylene in air. Ind Eng Chem Res 2017, 56: 12520–12528.
[12] Fariati P, Hashisho Z. Carbon nanotube growth on zeolite Y to tailor its electric resistivity for resistive heating regeneration. Micropor Mesopor Mater 2019, 277: 171–178.
[13] Dou LG, Yan CJ, Zhong LS, et al. Enhancing CO2 methanation over a metal foam structured catalyst by electric internal heating. Chem Commun 2020, 56: 205–208.
[14] Zhang L, Li TT, Quyn D, et al. Formation of nascent char structure during the fast pyrolysis of mallee wood and low-rank coals. Fuel 2015, 150: 486–492.
[15] Rieks M, Bellinghausen R, Kockmann N, et al. Experimental study of methane dry reforming in an electrically heated reactor. Int J Hydrogen Energy 2015, 40: 15940–15951.
[16] Zou N, Nie Q, Zhang XR, et al. Electrothermal regeneration by Joule heat effect on carbon cloth based MnO2 catalyst for long-term formaldehyde removal. Chem Eng J 2019, 357: 1–10.
[17] Knoll M, Schomäcker R, Bungert B. Catalytic activity of ceramic honeycombs in the exhaust gas oxidation of a waste treatment plant. Chem Eng Technol 2019, 42: 422–431.
[18] Knitter R, Liauw MA. Ceramic microreactors for heterogeneously catalysed gas-phase reactions. Lab Chip 2004, 4: 378–383.
[19] Witt SE, Allen AJ, Kuzmenko I, et al. In situ structural and electrical conductivity characterization of Sr2MnO4-s double perovskite solid oxide fuel cell anode materials. ACS Appl Energy Mater 2020, 3: 5353–5360.
[20] Yaremchenko AA, Macias J, Kovalyevsky AV, et al. Electrical conductivity and thermal expansion of Ln-substituted SrTiO3 for solid oxide cell electrodes and interconnectors: The effect of rare-earth cation size. J Power Sources 2020, 474: 228531.
[21] Shao X, Dong DH, Parkinson G, et al. Improvement of oxygen permeation through microchannelled ceramic membranes. J Membr Sci 2014, 454: 444–450.
[22] Zhao ZB, Ma YY, Sun WG, et al. Ceramic microchannel reactors with channel sizes less than 100 µm prepared by a mesh-assisted phase-inversion process. Ceram Int 2021, 47: 25485–25490.
[23] Li TP, Wang TP, Wei T, et al. Robust anode-supported cells with fast oxygen release channels for efficient and stable CO₂ electrolysis at ultrahigh current densities. Small 2021, 17: 2007211.

[24] Abdulhameed MA, Othman MHD, Al Joda HNA, et al. Fabrication and characterization of affordable hydrophobic ceramic hollow fibre membrane for contacting processes. J Adv Ceram 2017, 6: 330–340.

[25] Shao X, Dong DH, Parkinson G, et al. Improvement of oxygen permeation through microchanneld ceramic membranes. J Membr Sci 2014, 454: 444–450.

[26] Dey S, Dhal GC, Mohan D, et al. Low-temperature complete oxidation of CO over various manganese oxide catalysts. Atmos Pollut Res 2018, 9: 755–763.

[27] Park JH, Kang DC, Park SI, et al. CO oxidation over MnO₂ catalysts prepared by a simple redox method: Influence of the Mn (II) precursors. J Ind Eng Chem 2015, 25: 250–257.

[28] Xi YJ, Ren JC. Design of a CO oxidation catalyst based on two-dimensional MnO₂. J Phys Chem C 2016, 120: 24302–24306.

[29] Nielsen J, Hjalmarsson P, Hansen MH, et al. Effect of low temperature in situ sintering on the impedance and the performance of intermediate temperature solid oxide fuel cell cathodes. J Power Sources 2014, 245: 418–428.

[30] Bowman WJ, Zhu JT, Sharma R, et al. Electrical conductivity and grain boundary composition of Gd-doped and Gd/Pr co-doped ceria. Solid State Ion 2015, 272: 9–17.

[31] Li H, Liu YS, Liu YS, et al. Effect of sintering temperature in argon atmosphere on microstructure and properties of 3D printed alumina ceramic cores. J Adv Ceram 2020, 9: 220–231.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made.

The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.