



Preparation of nickel-foam-supported Pd/NiO monolithic catalyst and construction of novel electric heating reactor for catalytic combustion of VOCs

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ABSTRACT

Metal-based monolithic catalysts have excellent electrical and thermal conductivity, impact resistance, ductility, and mechanical properties. Thus, they have a broader application prospect than ceramic-based monolithic catalysts. In this work, high-dispersion Pd nanoparticle dispersion liquid was synthesized by using the solvothermal method. Moreover, nickel-foam-supported Pd/NiO (Pd/NiO/Ni foam) monolithic catalyst with good catalytic combustion performance was prepared successfully by simply spraying the dispersion liquid on the surface of Ni foam, which was oxidized at high temperature to grow NiO film. A novel electric heating catalytic combustion reactor with fast response and safety was constructed by nesting Pd/NiO/Ni foam with an insulated heating rod. Notably, even at the high space velocity of $50,000 \text{ h}^{-1}$, the constructed reactor can completely degrade 2500 ppm of toluene at $230 \text{ }^\circ\text{C}$ and exhibits good catalytic activity for hydrocarbons and oxygen-containing and heteroatom-containing organic compounds.

1. Introduction

Air pollution has aroused widespread public concern because it is the biggest environmental problem that threatens human and ecological balance [1–3]. Volatile organic compounds (VOCs) are a type of atmospheric pollutants that are extremely harmful. They are not only highly toxic, but also the key precursors of PM_{2.5} and O₃ and the major source of haze and photochemical smog [4,5]. Therefore, controlling VOCs pollution is an important part of improving air quality. Among numerous VOCs treatment technologies, catalytic combustion is widely used because of its advantages of low light-off temperature, wide application range, no secondary pollution, and good environmental and economic benefits [6–9]. The catalyst is core of the catalytic combustion technology. So far, noble metal catalysts are still the mainstream of application because of their excellent catalytic activity, selectivity, and universality. To reduce the cost of noble catalysts and maintain high activity and stability, trace amounts of noble metals are often supported on inexpensive redox carriers to take advantage of the interaction and synergistic effects between the two materials [10–12]. Cargnello et al. prepared the core-shell structure of Pd@CeO₂ to enhance the interaction between oxide and Pd, which could improve the activity and stability of the catalytic combustion of methane [13]. Seeburg et al.

prepared a series of highly active Pd/MeOx (Me = Fe, Co, Ni) catalysts for the catalytic combustion of methane, and research shows strong interaction between Pd and metal oxides [14]. Chen et al. found that the cooperative catalysis between Pt and NiO would improve the hydrogen evolution reaction (HER) activity in comparison with Pt solely.

However, the monolithic catalysts are the most widely used in treating industrial waste gases because of their advantages, such as good mass transfer performance, low pressure-drop, good thermal stability, and high mechanical strength. Ceramics and metals are commonly used carriers for monolithic catalysts. Compared with ceramic carriers, metal ones have better heat transfer properties, lower pressure-drop, and higher mechanical strength, thereby occupying an increasingly important position in reactions, such as catalytic combustion [15–18]. Among them, foam metal has attracted much attention because of its excellent thermophysical and mechanical properties [19–24], such as: (i) the irregular pores improve mass and heat transfer and trigger turbulent flow in the combustor chamber; (ii) the interconnected cell structure of metal foam reduces the pressure drop significantly, therefore allows for the more compact devices; (iii) the high thermal conductivity of metals favors to eliminate the hot/cold spots and reduce the temperature gradient of the strongly exothermic combustion; (iv) the metal foams can be easily shaped to fit various

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configurations of microreactors. However, especially for the preparation of metal-based monolithic catalysts, the traditional preparation process is relatively cumbersome, and the prepared catalyst has the issues of low dispersion and poor adhesion of active components, which seriously affect the catalytic activity and stability. On these issues, we reported a facile strategy for preparing monolithic catalysts by using the dispersion-liquid-spraying method [25–27]. This preparation strategy focuses on the following points: preparing the nanoparticle dispersion liquid with excellent combustion catalytic activity by using solvothermal method and by spraying the dispersion liquid on the different substrates to obtain monolithic catalysts. This strategy can make the active nanoparticles be flexibly and firmly loaded on the surface of the substrate and highly dispersed so that the prepared catalyst has satisfactory catalytic performance. Moreover, the use of this method can reactivate the catalyst when deactivated through respraying without replacing the monolithic catalyst. This process minimizes hazardous waste generation and the costs of preparation and operation greatly.

In this work, we used nickel foam as the carrier was oxidized at high temperature to grow NiO film (NiO/Ni foam). Then, the active Pd nanoparticle dispersion liquid was sprayed to prepare the nickel-foam-supported Pd/NiO monolithic catalyst (Pd/NiO/Ni foam), whose physical and chemical properties and catalytic toluene combustion performance have been evaluated. Taking advantage of the high thermal conductivity and easily forming of foam metal, a novel electric heating catalytic combustion reactor was constructed with Pd/NiO/Ni foam as the core, which was expected to provide a new approach for the control of VOCs in small- and medium-sized enterprises (SMEs) with intermittent production and capital shortage.

2. Experimental

2.1. Chemical agents

Palladium chloride (PdCl₂) was purchased Shanghai Chemical Reagent Co., Ltd. Oleylamine (C₁₈H₃₇N) and Oleic acid were purchased Shanghai Aladdin Biochemical Technology Co., Ltd. Ethanol (C₂H₆O) was purchased Anhui Ante Food Co., Ltd. Hexane (C₆H₁₄) was Shanghai Lingfeng Chemical Reagent Co., Ltd. Ni foam was purchased Kunshan Jiangteng Electronic Technology Co., Ltd.

2.2. Catalyst preparation

Synthesis of Pd nanoparticle dispersion liquid: 35.2 mg palladium chloride was mixed with 6 mL oleylamine and 2 mL oleic acid in a three-necked flask. In the N₂ atmosphere, the mixture was heated to 180 °C for 3 h with magnetically stirred. After the reaction, ethanol was added to the cooled solution to induce the precipitation of the nanoparticles, which were separated from the solvent by centrifugation at 6000 rpm for 5 min. The precipitation dispersed in hexane, and then repeat the above operations several times. Finally, the resulting precipitation re-dispersed in hexane to form Pd nanoparticle dispersion liquid.

Pretreatment of nickel foam: Put the nickel foam (Ni foam, thickness 10 mm, porosity 90 %) in acetone with ultrasonic treatment for 30 min to remove the oil on the surface, then rinse it with deionized water and dry it at 110 °C for 2 h. Finally, it calcined at 950 °C for 3 h in the O₂ atmosphere was labeled NiO/Ni foam.

Preparation of nickel-foam-supported Pd/NiO monolithic catalyst: A certain amount of Pd nanoparticle dispersion liquid was sprayed on the NiO/Ni foam. The resulting NiO/Ni foam with 0.1 wt% Pd dried at 110 °C for 2 h and calcined at 500 °C for 3 h in air atmosphere was labeled Pd/NiO/Ni foam.

2.3. Catalyst characterization

A Tecnai F30 S-Twin transmission electron microscope working at 300 kV was used for transmission electron microscopy (TEM). Samples for TEM investigation were prepared by dropping Pd dispersion liquid onto a carbon-coated copper grid.

Scanning electron microscopy (SEM) images and energy dispersive spectrometer (EDS) were obtained on a Hitachi S-4700(II) microscope operating at 15.0 kV.

X-ray diffraction (XRD) patterns were recorded on a PANalytical X'Pert PRO diffractometer instrument operated at 40 kV and 30 mA, with Cu K α -ray radiation ($\lambda = 1.54178 \text{ \AA}$). Scans were taken with a 2θ range from 10° to 100°.

Adhesion test was conducted by immersing the monolithic catalyst in deionized water inside a beaker and vibrating in an ultrasonic vibration instrument (40 kHz/100 w) for 30 min. Mass loss was calculated according to the mass of the sample before and after ultrasonic vibration.

H₂ temperature-programmed reduction (H₂-TPR) was measured on a FINE SORB-3010 E instrument equipped with a thermal conductivity detector (TCD). The sample was placed in a quartz reactor, pre-treated in Ar flow at 200 °C for 1 h and cooled down at 60 °C. The catalyst bed was performed by admitting a flow of 5 vol% H₂/Ar at 60 °C for 10 min, followed by heating at a constant rate (10 °C min⁻¹) up to 800 °C. Finally, the catalyst was cooled under the Ar flow. The flow rates in the experiment were 30 mL min⁻¹. Hydrogen consumption was monitored using TCD operated at 60 °C and 60 mA.

2.4. Catalytic activity test

Pd/NiO/Ni foam activity test: The combustion of toluene activity over Pd/NiO/Ni foam catalyst was evaluated with a continuous flow-fixed bed reactor. The feed consists of 2500 ppm toluene was generated by bubbling standard air through a bottle that contained pure toluene placed in an ice-water mixture (0 °C) and the gas hourly space velocity (GHSV) was 3000 h⁻¹. The concentrations of the toluene were detected by a gas chromatograph (Jet Island GC1620) equipped with FID. The conversion of toluene was calculated based on the concentration before and after the reaction.

Evaluation of reactor performance: The organic gas was generated by bubbling standard air through a bottle contained pure VOCs placed in a constant temperature water bath, and mixed with another dilution air to obtain a certain concentration and space velocity of simulated organic waste gas, which entered the reactor as shown in Fig. 7a (the specific details shown in Fig. S1 and its description). The concentration of exhaust gas was detected by a gas chromatograph (Jet Island GC1620) and mass spectrometry (Cirrus 2). The conversion was calculated based on the organic waste gas concentration before and after the reaction.

3. Results and discussion

3.1. Dispersion of Pd nanoparticle dispersion liquid

Pd/NiO/Ni foam monolithic catalyst was prepared using an active nanoparticle dispersion liquid spray method. The active nanoparticle dispersion liquid is the key component of this method. Thus, the synthesis of Pd nanoparticles with small size and good dispersibility is crucial. Fig. 1a shows the synthesized Pd nanoparticle dispersion liquid. The dispersion liquid is black, uniform, and has good dispersibility. TEM characterization was used to investigate the dispersion state of Pd nanoparticles in the liquid further, and the results are shown in Fig. 1b~e. The Pd nanoparticles were relatively uniform in size (2~5 nm) and had good dispersibility. The aforementioned characterization showed that satisfactory nano-Pd dispersion liquid was successfully synthesized to provide favorable conditions for the subsequent

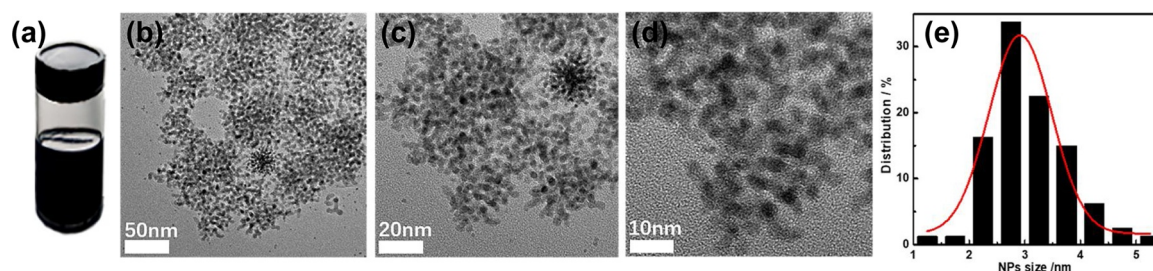


Fig. 1. Photograph (a), TEM images (b~d) and size histograms (e) of nano-Pd dispersion liquid.

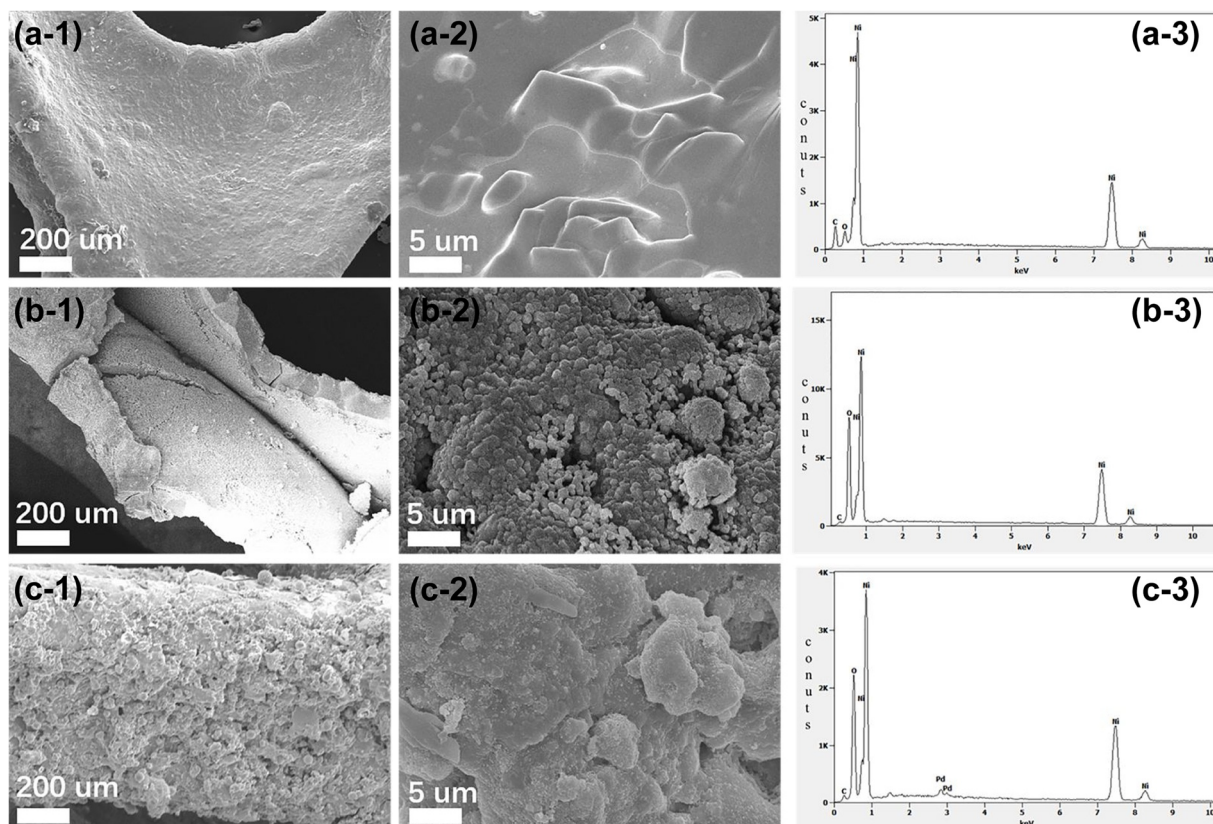


Fig. 2. SEM images and EDS results of (a) Ni foam, (b) NiO/Ni foam, and (c) Pd/NiO/Ni foam.

spray preparation of the Pd/NiO/Ni foam monolithic catalyst.

3.2. Surface structure and phase analysis of Pd/NiO/Ni foam monolithic catalyst

In this work, the nickel foam substrate was oxidized at high temperature to grow NiO film in situ, which could provide a redox support for noble metal Pd. In addition, the surface of the metal carrier is smooth and does not have a porous structure (Fig. 2a-1, a-2) similar that of the ceramic carrier, which is not conducive to the loading of active components [28–31]. A study showed that NiO film could evenly disperse the noble metal nanoparticles deposited on the surface [15]. Therefore, the formation of NiO film on the surface of the nickel foam substrate is crucial for the successful preparation of nickel-foam-supported Pd/NiO monolithic catalyst. Fig. 2b-1 and b-2 show the SEM images of the nickel foam after heat treatment (Ni foam), in which the surface of Ni foam is covered by large numbers of nano-islands. From the EDS and XRD data (Fig. 2a-3, b-3, Table 1, and Fig. 3), this layer of nano-islands is a NiO film formed by the high-temperature oxidation of the surface Ni atoms. Thus, the high-temperature oxidation treatment of the nickel foam substrate is beneficial to the subsequent loading of Pd

Table 1

Atomic composition of Ni foam, NiO/Ni foam, and Pd/NiO/Ni foam determined by X-EDS.

Sample	Element	Weight /%	Atomic /%
Ni foam	C	22.75	55.75
	O	3.99	7.35
	Ni	72.95	36.57
NiO/Ni foam	C	1.63	5.44
	O	14.85	37.34
	Ni	83.52	57.22
Pd/NiO/Ni foam	C	2.02	6.58
	O	16.03	39.28
	Ni	79.99	53.42
	Pd	1.96	0.72

nanoparticles.

Pd nanoparticles can be highly dispersed in the dispersion liquid because of the presence of surfactants, such as oleylamine and oleic acid, the. Therefore, after spraying Pd nanoparticles on NiO/Ni foam, these organic compounds were removed by calcining to fully expose the active components. Fig. 2c-1 and c-2 show the SEM images of the

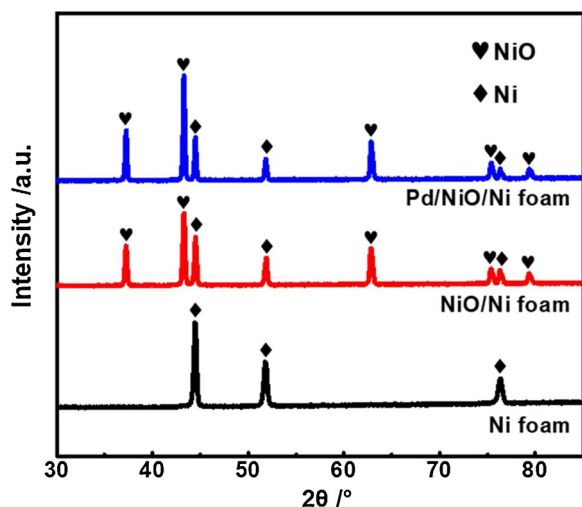


Fig. 3. XRD patterns of Ni foam, NiO/Ni foam, and Pd/NiO/Ni foam.

prepared Pd/NiO/Ni foam monolithic catalyst. The surface becomes fluffy and porous, which is due to more NiO was produced during the heat treatment to remove the surfactant (Fig. 2c-3, Table 1). Heterogeneous catalytic reaction is surface reaction. Therefore, it can be seen from SEM images (Fig. 2) and data of the specific surface area (Fig. S2) that NiO produced could provide a larger place for reaction. Besides increasing the surface area, the formation of NiO can also provide redox carrier for Pd to enhance its activity. The experimental results also confirm that NiO produced facilitating the VOCs catalytic combustion (Fig. S3). Although no characteristic peaks of Pd species were detected in the XRD of Pd/ NiO/Ni foam (Fig. 3), combined with EDS data, Pd nanoparticles have been successfully dispersed on the surface of the nickel foam substrate. For monolithic catalyst, the adherence of coating and active phase to the substrate is crucial, which was evaluated through adhesion test. The mass of Pd/NiO/Ni foam before and after ultrasonic bath is 0.8298 g and 0.8269 g. The loss rate is only 0.35 %, indicating that that NiO coating and Pd particles have adhered well to the Ni foam substrate. The toluene catalytic combustion performance of Pd/NiO/Ni foam before and after ultrasonic bath (Fig. S4) further shows the excellent adhesion of NiO coating and Pd particles.

3.3. Redox properties of Pd/NiO/Ni foam monolithic catalyst

The redox properties of Ni foam, NiO/Ni foam, and Pd/NiO/Ni foam were investigated using the H₂-TPR technique. The corresponding TPR profiles are shown in Fig. 4. Considering that Ni foam does not show any hydrogen consumption in the investigated temperature, the reduction peaks of NiO/Ni foam observed can be attributed to NiO species. Compared with NiO/Ni foam, the two reduction peaks in Pd/NiO/Ni foam are shifted towards lower temperatures, and the area ratio of the low-temperature reduction peak to the high-temperature reduction peak in Pd/NiO/Ni foam (0.47) is larger than that of the NiO/Ni foam (0.39). These results further indicate that Pd nanoparticles were successfully supported on the surface of the nickel foam by simply spraying and interacted with NiO, thus enhancing oxygen mobility.

The XPS spectrum of Pd 3d for the Pd/NiO/Ni foam was displayed in Fig. 5 to investigate the valence state of Pd which is related to the redox properties of Pd/NiO/Ni foam. Generally, the XPS spectrum of Pd 3d involves Pd 3d_{5/2} and Pd 3d_{3/2} with a spin-orbit splitting at ca. 5.3 eV [10]. As the figure shows that the Pd 3d spectrum of Pd/NiO/Ni foam displayed two peaks with binding energies of approximately 336.7 eV (Pd 3d_{5/2}) and 342.0 eV (Pd 3d_{3/2}), which were ascribed to the peaks of Pd(2+) [32–34]. For Pd/NiO/Ni foam, the Pd 3d spectrum only revealed the characteristic binding energies of Pd(2+). Combining related literature [14] and our previous work [35], this result indicates

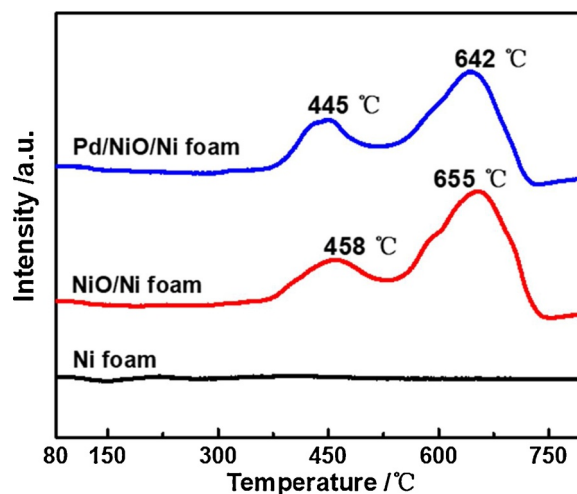


Fig. 4. H₂-TPR profiles of Ni foam, NiO/Ni foam and Pd/NiO/Ni foam.

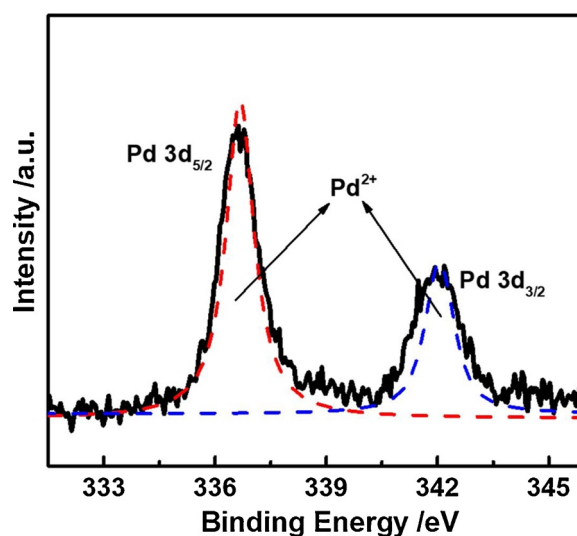


Fig. 5. XPS spectrum of Pd 3d for the Pd/NiO/Ni foam.

that there is an interaction between Pd and NiO, which would consequently turn Pd(0) into electro-deficient palladium and shift the reduction peaks of NiO to lower temperatures as shown in Fig. 4.

3.4. Catalytic activity of Pd/NiO/Ni foam monolithic catalyst

To understand the catalytic combustion performance of the prepared Pd/NiO/Ni foam, toluene was used as the target pollutant for evaluation. The results are shown in Fig. 6. Fig. 6a shows Ni foam and NiO/Ni foam have no catalytic activities, but the prepared Pd/NiO/Ni foam shows good catalytic performance. These results also indicate that Pd nanoparticles have been successfully supported on the surface of nickel foam by simply spraying. To further understand the catalytic activity of Pd/NiO/Ni foam, Pd/γ-Al₂O₃ with the same Pd loading was prepared according to the classical type of industrial catalyst formulation as a comparison, and the results are shown in Fig. 6b. Pd/NiO/Ni foam shows an equivalent catalytic activity to Pd/γ-Al₂O₃. And the long-time running stability test of Pd/NiO/Ni foam was evaluated at 240 °C with the result shown in Fig. 6c. Toluene conversion was maintained at about 40 % without significantly decrease during 30 h test. These results indicate that applying the Pd/NiO/Ni foam monolithic catalyst is feasible to VOCs catalytic combustion, which provides support for the construction of a novel electric heating catalytic combustion reactor that features Pd/NiO/Ni foam monolithic catalyst.

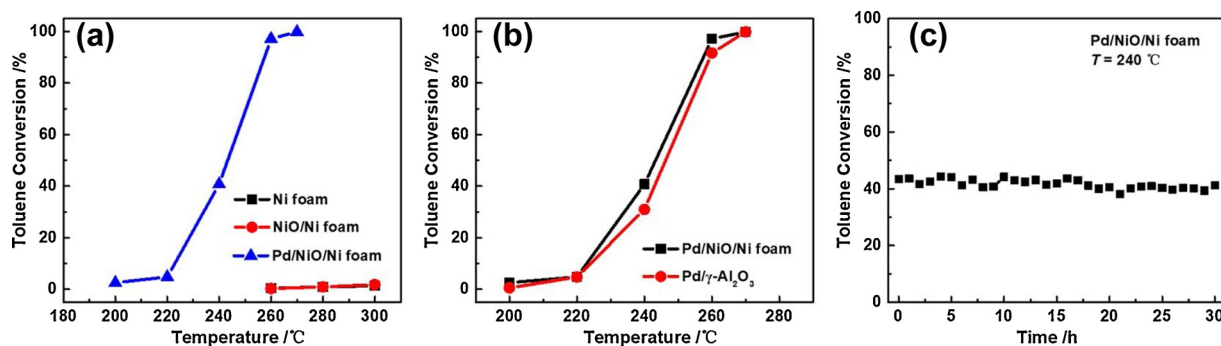


Fig. 6. (a) Toluene catalytic combustion performance of Ni foam, NiO/Ni foam and Pd/NiO/Ni foam; (b) Comparison of Toluene catalytic combustion performance over Pd/NiO/Ni foam and Pd/Al₂O₃; (c) Stability test of Pd/NiO/Ni foam for toluene catalytic combustion. Reaction conditions: 2500 ppm Toluene, GHSV = 3000 h⁻¹.

3.5. Performance of novel electric heating reactor featuring Pd/NiO/Ni foam monolithic catalyst

The traditional VOCs catalytic combustion device needs to be preheated each time it runs. Moreover, the entire equipment includes a catalytic tank, heating tank, and some accessories such as pipes. The cost and land occupation of traditional VOCs catalytic combustion devices are large. Therefore, it is not suitable for the SMEs with small VOCs emissions, intermittent production, and capital shortage. To solve the problem of VOCs governance in SMEs, we have made some explorations. For example, we reported that loading Pt or Pd nanoparticles on FeCrAl metal wire can convert VOCs quickly and completely under a low-current DC power by using self-heated electrically [35]. The use of the electric heating function of metal-based monolithic catalysts could effectively reduce the volume of a catalytic combustion device and enable the catalyst to heat up and respond rapidly [36–42]. Such properties could improve the utilization rate of thermal energy and reduce energy consumption. Given these features, metal-based monolithic catalysts could provide a solution to the issues of high energy consumption and cost in the VOCs governance of SMEs. However, applying a voltage directly to bare metal-based catalysts for heating could lead to safety problems [43], especially in actual complex exhaust gas environments. Therefore, the construction of a fast-responsive, safe and durable catalytic combustion system is particularly important to help solve the problem of VOCs governance in SMEs.

The aforementioned characterization and test results indicate that the Pd/NiO/Ni foam monolithic catalyst with good performance was

successfully prepared by using active nanoparticle dispersion liquid spray method. Considering the characteristics of high thermal conductivity and easy to form foam metal, we construct a novel electric heating catalytic combustion reactor (Fig. 7a) using Pd/NiO/Ni foam monolithic catalyst and insulated heating rod, and the heating-up characteristic of Pd/NiO/Ni foam in the reactor was tested (Fig. 7b). As shown in Fig. 7b, the temperature of the catalytic bed increased rapidly because of the energizing heating rod, which could increase from room temperature to 300 °C within 150 s under different experimental conditions. Although this rate is not as fast as the heating rate of self-energized metal-based catalysts, the fast startup, greater safety, and durability could be achieved. Notably, the temperature increased faster with the space velocity. The time required for the Pd/NiO/Ni foam to heat up from room temperature to 300 °C was reduced by 30 s when the space velocity increases from 0 h⁻¹ to 50,000 h⁻¹. This rapid heating rate could be attributed to the foam metal, which had high porosity and a large specific surface area. It could also easily exchange heat with the surrounding airflow [44–46]. When the reactor was energized, the heat generated by the heating rod can be transferred to the nickel foam (1 piece is Pd/NiO/Ni foam, 9 pieces are Ni foam; the details in Supplementary Material), which can heat the surrounding airflow. Thus, the function of 9 pieces Ni foam without catalytic activity near the gas inlet is to transfer the heat generated by the heating rod to the exhaust gas, which coupled with the heating rod heats the Pd/NiO/Ni foam near the gas outlet, and the heating rate of the catalytic bed increases with the flow rate increases. This structure of the heating rod completely covered by the nickel foam can make full use of the heat generated by the

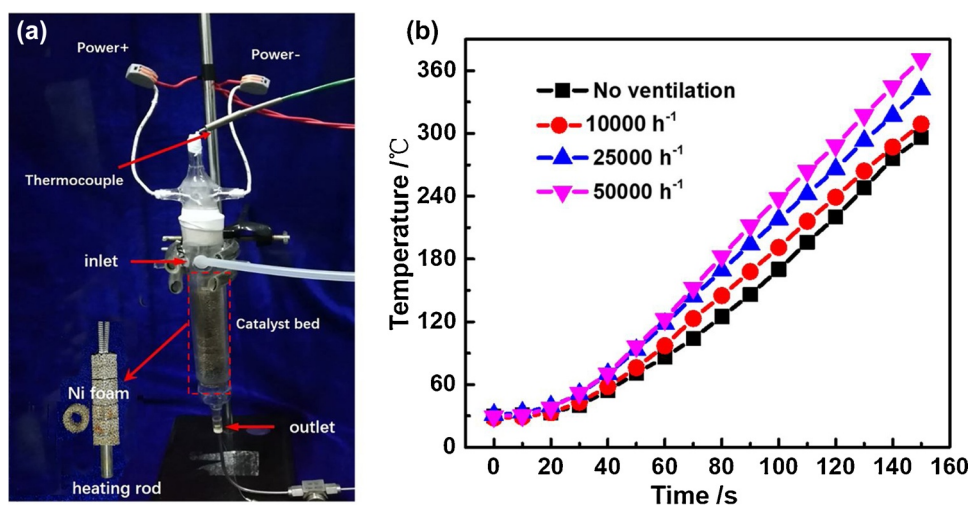


Fig. 7. (a) Photograph of novel electric heating catalytic combustion reactor; (b) Temperature rise characteristic of Pd/NiO/Ni foam in the reactor under different space velocities.

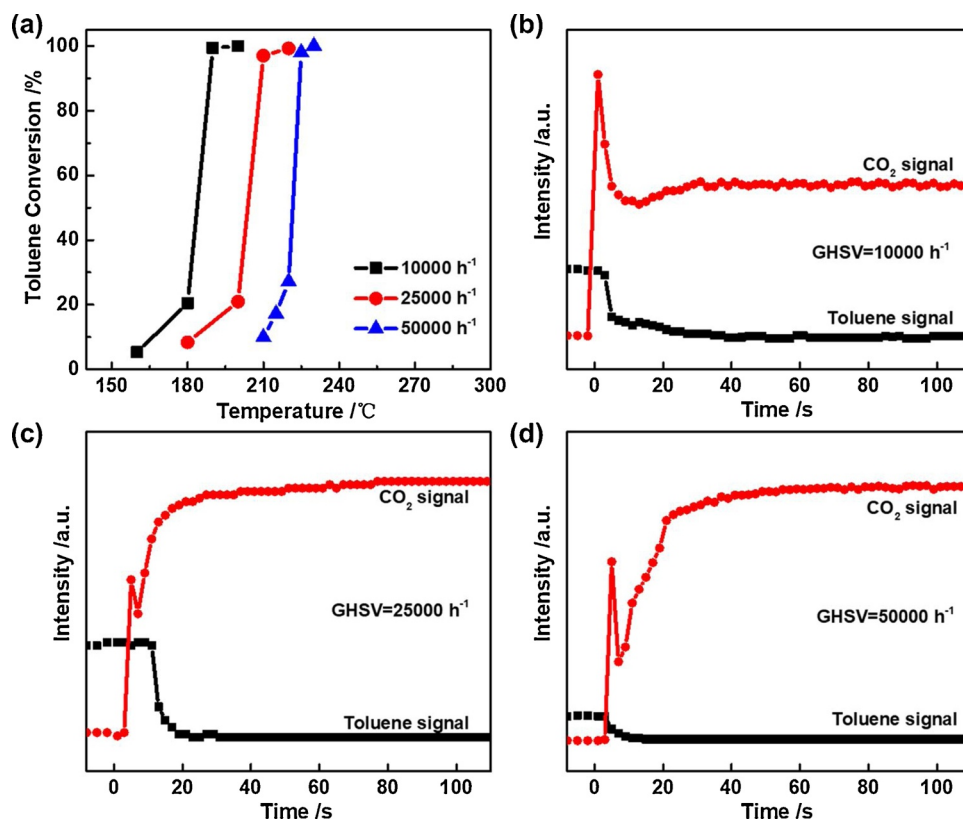


Fig. 8. (a) Light-off curves and (b-d) mass spectrometry tested curves of toluene catalytic combustion over the electric heating reactor featuring Pd/NiO/Ni foam monolithic catalyst under different space velocities. Reaction conditions: 2500 ppm Toluene. (CO₂ in the air which be introduced into the reactor during the assembly process cause the spike in CO₂ signal at the beginning in b~d).

heating rod to heat the exhaust gas and catalytic bed, which can make the reactor reach the working temperature rapidly at a low energy consumption. Moreover, it could be adapted to high space velocity environments.

Industrial exhaust emissions are generally produced in massive volumes. Hence, space velocity is an important parameter that must be considered in the practical application of catalysts [47,48]. The catalytic combustion performance of the constructed novel electric heating reactor for toluene was investigated under high space velocity conditions, and the results are shown in Fig. 8. Fig. 8a shows that an increase in space velocity caused the light-off curve to move toward the high-temperature direction because the increase in space velocity reduces the residence time of the waste gas in the reactor and the reaction conversion rate. Therefore, increasing the reaction temperature to accelerate the reaction rate is necessary to convert toluene over a short residence time completely. Despite this, by using the constructed electric heating catalytic combustion reactor, toluene can be completely converted at a low temperature (230 °C) even at a high space velocity of 50,000 h⁻¹, which can be attributed to the unique 3D network structure of the metal foam that allows sufficient contact between the reactants (toluene, oxygen) and active components even at high space velocity conditions. To understand whether the constructed novel electric heating catalytic combustion reactor can respond quickly, the tail gas of the reactor (the temperature of the reactor is 250 °C to ensure the complete combustion of toluene) was monitored by mass spectrometry in real-time (Fig. 8b~d). After the toluene simulation gas with different space velocities through the reactor, the toluene signal decreases rapidly, and CO₂ signal increases rapidly. Even at a high space velocity of 50,000 h⁻¹, toluene was completely burned after approximately 30 s. Therefore, the constructed novel electric heating catalytic combustion reactor can be quickly responded to degrade the VOCs without preheating for a long time. For intermittent production conditions, the reactor only needs to be power on a few minutes before the startup of the production equipment, and then be power off after the shutdown of production equipment. This can greatly reduce the

operating cost of the reactor while ensuring the treatment effect of VOCs.

The composition of VOCs waste gas is complex. To understand the applicability of the constructed electric heating catalytic combustion reactor for VOCs catalytic combustion, its catalytic combustion activity for benzene, chlorobenzene, DMF, pyridine and acetone was tested (Fig. 9). The results show that the electric heating reactor that features Pd/NiO/Ni foam monolithic catalyst has good catalytic activity for hydrocarbons and oxygen-containing and heteroatom-containing organic compounds, which can be completely converted at a relatively low temperature (< 300 °C). This result shows that the prepared Pd/NiO/Ni foam monolithic catalyst can be used for the catalytic combustion of different types of VOCs. Overall, the constructed electric

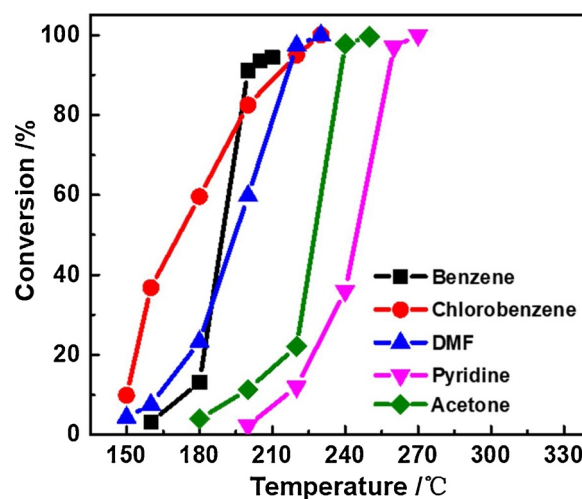


Fig. 9. Different VOCs catalytic combustion performance over the electric heating reactor featuring Pd/NiO/Ni foam monolithic catalyst. Reaction conditions: 2500 ppm VOCs, GHSV = 10,000 h⁻¹.

heating catalytic combustion reactor has good VOCs catalytic combustion activity and stability (Fig. S5). This catalyst can make full use of the heat generated by the heating rod, so that the catalytic bed and exhaust gas can reach the working temperature rapidly. Therefore, this catalytic combustion reactor is promising for the management of VOCs in SMEs with intermittent production and capital shortage.

4. Conclusions

In this work, Pd nanoparticle dispersion liquid with high dispersion and size of 2~5 nm is synthesized by using the solvothermal method. Moreover, a series of characterization and test results show that the Pd/NiO/Ni foam monolithic catalyst with good performance is prepared successfully by simply spraying the Pd nanoparticle dispersion liquid on the surface of high-temperature treated nickel foam. Pd/NiO/Ni foam is nested with a heating rod to construct a novel electric heating catalytic combustion reactor. The test results of the heating-up characteristics show that the good thermal conductivity and unique three-dimensional network structure of the nickel foam carrier can make full use of the heat generated by the heating rod to enable the system to reach the light-off temperature rapidly and achieve the purpose of rapid response. Performance test results show that the reactor has good activity and stability of VOCs catalytic combustion. Therefore, this work provides a new direction for the research and application of foam metal-based monolithic catalysts. Particularly, the constructed novel electric heating catalytic combustion reactor has the characteristics of small size, rapid response, high catalytic activity, and safety, thereby providing a new approach for the control of VOCs in SMEs with intermittent production and capital shortage. This study has considerable application prospect and is worthy of further industrial research.

CRediT authorship contribution statement

Xiao Chen: Methodology, Validation, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Jianguo Li:** Data curation, Methodology, Validation, Investigation. **Yue Wang:** Data curation, Methodology, Validation. **Ying Zhou:** Conceptualization, Resources, Data curation, Supervision. **Qiulian Zhu:** Formal analysis, Project administration. **Hanfeng Lu:** Conceptualization, Data curation, Methodology, Resources, Writing - review & editing, Supervision, Writing - original draft, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.apcata.2020.117839>.

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