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Surface modification of a low-density ceramic for gas–solid separation

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ABSTRACT

The surface of low-density ceramic (LDC) material was modified by using high-viscosity silica sol. The optimal preparation parameters for the sol were obtained using an orthogonal experimental design. The influence of the drying condition on the coating quality and even on the value of fine particulate matter after filtering ($VFPM_{2.5}$) was studied. The coating morphology was characterized by using scanning electron microscope (SEM). The results indicate that the $VFPM_{2.5}$ decreased from 25.2 μg/m^3 to 0.3 μg/m^3. The regeneration performance of the LDC filter elements was significantly improved by the surface modification. The baseline pressure drop using the LDC with the coating is less than 138.61 Pa. The results show that the coating makes a negligible effect on the pressure drop in comparison with the conventional method of modification. Moreover, the LDC with the coating demonstrated great isothermal oxidation performance and thermal shock resistance during the filtration process.

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1. Introduction

Air pollution has become a serious public health issue. Fine particle mass (particulate matter ≤ 2.5 μm; $PM_{2.5}$) constitutes one of the primary forms of air pollutants. Particulate matter often contains toxic components hazardous to human health [1,2]. $PM_{2.5}$ emissions are primarily from the high-temperature emission of various industrial plants, such as thermal power plants, cement factories, metallurgy activities, and the steel industry. There are various technologies to control the particulate matter created by industrial processes. For example, the electrostatic precipitators, fabric filters, and cyclone dust collectors have been utilized in power plants and cement plants [3–5]. A significant improvement in the gas–solid separation and air purification has been achieved in recent years by the use of low-density ceramic (LDC) filter elements fabricated by ceramic fibers [6,7]. LDC filter elements offer the major advantage of relatively low differential pressure and good thermal shock resistance [8]. LDC filters can be operated at high temperature (600 °C) which minimizes the energy loss by avoiding the cooling of raw product gas. However, the value of fine particulate matter after filtering ($VFPM_{2.5}$) and regeneration performance of LDC filters are barely adequate. Therefore, the performance enhancement of LDC filter elements is essential for their use in applications. Surface modification of LDC filter elements is an effective method for the improvement of their performance.

Nowadays, there are many processing methods or techniques used in surface modification. The traditional methods involve the sol–gel method [9], as well as the foam coating method [10]. Furthermore, some advanced processes such as replica technique/sponge replication technique [11], atomic layer deposition (ALD) [12], particle-stabilized direct foaming technique [13,14] and foaming method combined with sol–gel technology [15]. For modification on the surface of LDC, the sol–gel method is the most suitable technique among these methods. The advantages of the sol–gel method are simple operation, without the involvement of polymer and no restriction on the type of the substrate [9–15] in comparison with the above advanced processes. However, according to previous work [16–19], the pressure drop of LDC had a significant increase after coating with low-viscosity sol.

In this study, we described a method of coating with high-viscosity sol on LDC surface. Low-viscosity sol is easy to penetrate into the porous structure because of the hydrophilic surface of LDC. But high-viscosity sol is firmly adhered on the LDC surface. The difference from previous work is to achieve a lower pressure drop and a better separation performance by using high-viscosity sol. However, the high-viscosity may cause the nonuniformity of coating. Thus, in order to prepare the coating with high quality, it is crucial to control the viscosity of the sol and keep the uniformity of coating. This is the aim of this work. The suitable viscosity of sol was ascertained by the analysis of the relationship between the sol viscosity and the pressure drop of the LDC with the coating. The optimal preparation parameters of silica sol were determined by an orthogonal array experiment. The drying conditions and heating procedure for the coating were examined in detail. Moreover, the high temperature performance and the regeneration performance of the LDC filter elements were measured.

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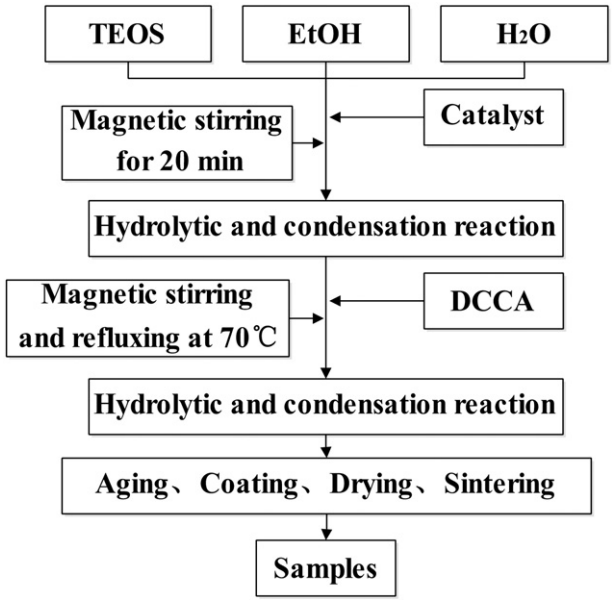

Fig. 1. Sol–gel process for SiO_2 coating.

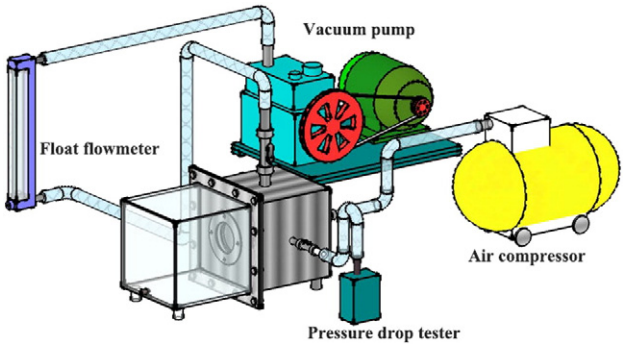

Fig. 2. The experimental apparatus diagram of regeneration performance experiment.

2. Experimental

2.1. Surface modification of LDC

The LDC filters in this paper were all homemade. The LDC was prepared from aluminum silicate fibers and an inorganic adhesive. It was a kind of porous ceramic fiber filter material prepared by the vacuum filtration method. And the preparation process of LDC includes mixing, vacuum filtering, demolding, drying and sintering [20].

The process of surface modification was demonstrated in Fig. 1. First, ethyl orthosilicate (TEOS), deionized water (H_2O) and ethanol (EtOH) were placed in a three-mouth flask with stirring at room temperature. After adding diluted hydrochloric acid (HCl) drop-wise into the mixture, N,N-dimethyl formamide (DMF) was added as a drying control agent. Next, the mixture was stirred and refluxed at 70 °C for 2.0, 2.5, or 3.0 h, and then aged for a period ranging from 4.5 h to 387.5 h. After aging, the silica sol was coated onto the surface of the LDC by spin-coating at the rotating speed of 2000 rpm. Subsequently, the coating was dried at 20 °C, followed by thermal treatment in a high temperature furnace.

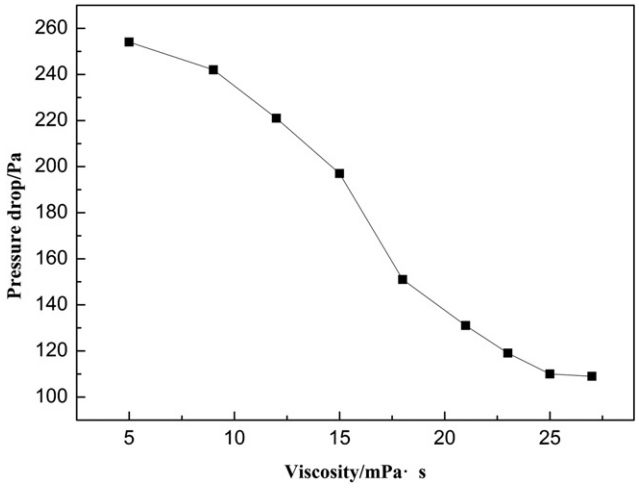

Fig. 3. The influence of sol viscosity on the pressure drop of LDC with coating.

2.2. Characterization

The thickness and the surface morphology of the coating were characterized by using a scanning electron microscope (SEM, JSM-5900). The viscosity of the sol was measured by using an R/S rheometer. The simultaneous thermal analyses of TG (thermogravimetry) and DSC (differential scanning calorimetry) were conducted using a NETSCH thermal analyzer STA 449C. The SiO_2 xerogel was heated from 20 °C to 900 °C at a rate of 10 °C/min under a gas stream of $N_2/O_2 = 75/25$. The $VFPM_{2.5}$ was tested by using an air filter efficiency instrument (CW-HAT200). The pressure drop of the filters was tested according to the Chinese standard "test method of the performance of high efficiency particulate air filters" (GB/T 6165-2008). The regeneration performance of the filters was determined using a homemade device under a simulated industrial environment. The experimental apparatus diagram is shown in Fig. 2. The procedures used are described as follows. The initial pressure drop of the filter elements was detected. Next, the air filtration was processed. The dust on the surface of filters was removed by pulse blowback at a frequency of 5 min/time. After performing the pulse blowback five times, the residual pressure drop of the filters was recorded. The isothermal oxidation tests were performed in air under atmospheric pressure. The temperature was held at 600 °C for 1 h, 5 h, 24 h, and 48 h. The thermal shock test was conducted as follows. The filters were heated to 600 °C and held for 20 min and then quenched in cool air. The thermal shock performance was tested ten times for each sample. The change of the $VFPM_{2.5}$ was measured during the isothermal oxidation and thermal shock tests.

3. Results and discussion

3.1. The suitable viscosity of the sol for coating

The LDC was prepared from aluminum silicate fibers and an inorganic adhesive. The structural parameters of the LDC are listed in Table 1. Evidently, the sol with low-viscosity can easily penetrate deeply into the

Table 1
Structural parameters of the LDC.

Diameter/mm	Thickness/mm	Pore size/μm	Water absorption/%	Porosity/%	Pressure drop/Pa	$VFPM_{2.5}$ /(μg/m^3)
72–73	6.0–6.5	20–80	100–130	70–80	65–67	25.2–26.3

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