Journal of Hazardous Materials B136 (2006) 747–756

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Development of a double-layered ceramic filter for aerosol filtration at high-temperatures: The filter collection efficiency

Normanda L. de Freitas [a], José A.S. Gonçalves [a], Murilo D.M. Innocentini [b], José R. Coury [a,*]

[a] Chemical Engineering Department, Federal University of São Carlos, Via Washington Luiz, km 235, 13565-905 São Carlos, SP, Brazil

[b] Chemical Engineering Department, University of Ribeirão Preto, Av. Costábile Romano, 2201 Ribeirânia, 14565-380 Ribeirão Preto, SP, Brazil

Received 7 October 2005; received in revised form 22 December 2005; accepted 11 January 2006

Available online 8 February 2006

Abstract

The performance of double-layered ceramic filters for aerosol filtration at high temperatures was evaluated in this work. The filtering structure was composed of two layers: a thin granular membrane deposited on a reticulate ceramic support of high porosity. The goal was to minimize the high pressure drop inherent of granular structures, without decreasing their high collection efficiency for small particles. The reticulate support was developed using the technique of ceramic replication of polyurethane foam substrates of 45 and 75 pores per inch (ppi). The filtering membrane was prepared by depositing a thin layer of granular alumina–clay paste on one face of the support. Filters had their permeability and fractional collection efficiency analyzed for filtration of an airborne suspension of phosphatic rock in temperatures ranging from ambient to 700 °C. Results revealed that collection efficiency decreased with gas temperature and was enhanced with filtration time. Also, the support layer influenced the collection efficiency: the 75 ppi support was more effective than the 45 ppi. Particle collection efficiency dropped considerably for particles below 2 μm in diameter. The maximum collection occurred for particle diameters of approximately 3 μm, and decreased again for diameters between 4 and 8 μm. Such trend was successfully represented by the proposed correlation, which is based on the classical mechanisms acting on particle collection. Inertial impaction seems to be the predominant collection mechanism, with particle bouncing/re-entrainment acting as detachment mechanisms.

Keywords: Gas cleaning; High temperature filtration; Collection efficiency; Ceramic filters

1. Introduction

Hot gas filtration has become increasingly important in cogeneration plants employed to provide heat, electricity or power. In such technologies based on gasification, biomass combustion and waste incineration processes, the flue gases must be previously cleaned to avoid damage to downstream equipments or components and also to meet environmental regulations [1–3].

There are several technologies for conventional gas cleaning, and the correct choice depends on the features of the process and the nature of the pollutant. In hot-gas based plants, however, the hostile atmosphere that contains small particles and frequently toxicant gaseous components, restrains the available options. Fabric filters and wet scrubbers demand the cooling of the gaseous stream, making unfeasible the recovery of energy, in this case the major product of the process. Cyclones can withstand high temperatures and are relatively cheap and easy to operate, but their particle collection efficiency is low for particles smaller than 10 μm, hardly meeting the rigorous emission regulations [4]. Electrostatic precipitators, on the other hand, are very efficient for small particles and can operate at high temperatures, but they are expensive and therefore unfeasible for small-scale plants [2].

The ability to withstand temperatures above 500 °C with high efficiency has made ceramic filters one of the most successful technologies for hot gas cleaning in the past 20 years. It has been shown to be an interesting alternative for a number of applications. For example, in diesel particulate control, ceramic filters coupled with carbon combustion catalysts have been successfully used [5–8]. Ceramic filters have also been used for hot gas cleaning in pressurized fluidized bed combustors [9–11] and in methanol and hydrogen production from biomass [12].

Ceramic filters for hot gas cleaning can be roughly divided in two main categories according to the structure of their

* Corresponding author. Tel.: +55 16 3351 8440; fax: +55 16 3351 8266.
E-mail address: jcoury@power.ufscar.br (J.R. Coury).

0304-3894/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2006.01.012

Nomenclature

A	filter face area exposed to fluid flow (m^2)
A_S	Happel's parameter
D	diffusion coefficient (m^2/s)
d_c	mean collector size (m)
d_p	dust particle size (m)
E_{over}	overall collection efficiency
E_{frac}	fractional collection efficiency
F_S	Cunningham slip factor
G	gravity acceleration (m/s^2)
K_B	Boltzmann's constant (kg m)/(s^2 K)
K	dimensionless parameter defined in Eq. (9)
k_1	Darcian permeability constant (m^2)
k_2	non-Darcian permeability constant (m)
L	filter thickness (m)
M_i	mass of particles in a given size range sampled at the filter entrance (kg)
M_o	mass of particles in a given size range sampled at the filter exit (kg)
N_i	Number of particles in a given size range sampled at the filter entrance
N_o	Number of particles in a given size range sampled at the filter exit
N_{Pe}	Peclet's number
N_{Re}	Reynolds' number
N_{St}	Stokes' number
$N_{St\,eff}$	effective Stokes' number
P	absolute pressure (kg/m s^2)
P_i	absolute inlet pressure (kg/m s^2)
P_o	absolute outlet pressure (kg/m s^2)
T	absolute temperature (K)
v_s	fluid velocity or filtration velocity (m/s)
v_t	terminal settling velocity (m/s)

Greek symbols

α_1–α_4	fitting constants in Eq. (23)
ε	porosity of the filter
γ	probability of adhesion
η_D	single collector efficiency due to diffusion
η_{DI}	single collector efficiency due to direct interception
η_E	single collector efficiency due to electrophoresis
η_G	single collector efficiency due to gravity
η_I	single collector efficiency due to inertia
η_T	total single collector efficiency
λ	mean free path of gas molecules (m)
μ_{air}	absolute air viscosity (kg/m s)
ρ_{air}	air density (kg/m^3)
ρ_p	dust particle density (kg/m^3)

constituents: fibrous filters and granule-bonded filters. Fibrous ceramic filters are made of alumina, aluminosilicates or zirconia filaments ranging from 2 to 20 μm in diameter. They have high porosity ($\varepsilon \cong 80$–95%), specific surface area ($S_o \cong 0.8$–1.5×10^6 m^2/m^3) and permeability ($k_1 \cong 10^{-15}$ to 10^{-10} m^2). Their collection efficiency is very high and the pressure drop low, but they suffer from relatively low mechanical strength.

Granular filters, on the other hand, are made of alumina, silicon carbide, aluminosilicates, silica, mullite granules or a combination of them stuck together by ceramic binders. Similarly to fibrous filters, they can withstand hostile atmospheres and high temperatures and pressures. Their porosity ranges between 40–60%, giving a good mechanical strength but a relatively low permeability [13,14].

In recent years, a new category of ceramic filter has gained ground: the double-layered filters [15–17]. Each layer can be optimized according to the desired requirements, combining in one product the best features of both fibrous and granular filters. The support layer is made of a highly porous ceramic foam, which provides good mechanical integrity, resistance to thermal cycling and almost no resistance to gas flow [18]. The filtering layer, on the other hand, is made of a thin granular membrane deposited on one surface of the support layer, providing a physical barrier to collect small particles with a minimum pressure drop [2,3].

The objective of this work is to investigate the performance of a double-layered filter for aerosol filtration at high temperatures. Laboratory tests included measurement of permeability and fractional collection efficiency in different temperatures and filtration times.

2. Experimental procedure

2.1. Sample preparation

Ceramic supports were prepared by the replication technique from the impregnation of a ceramic slurry of water, alumina (A3000FL, Alcoa, Brazil) and dispersant (Darwan 7s) into polyurethane foam matrices (Bulpren R, Sidney Heath & Son, Stoke-on-Trent, UK) of 45 and 75 pores per linear inch (ppi). Support samples, disks with diameter of 6.6 cm and thickness of about 1.8 cm, were sintered in an electric furnace at 1600 °C for 2 h.

The filtering layer was prepared from a ceramic paste, consisted of 20 wt% water and 80 wt% solids (75 wt% fused alumina (+80–70 mesh), 25 wt% ball clay (−200 mesh) and sodium silicate as binder. The ball clay utilized (São Simão) had approximately 45% of SiO_2, 33.5% Al_2O_3, 1.5%Fe_2O_3 and 1.3% TiO_2 [19].

One millimeter of paste was deposited on one face of each sintered support and then the whole structure was dried and heated to 1400 °C to provide a good adhesion of both layers. The heating procedure was as follows:

- oven at ambient pressure and open to the atmospheric air;
- heating rate of 2 °C/min;
- 120 min at 700 °C;
- 120 min at 1400 °C.

Fig. 1 shows a SEM micrograph of the cross section of a 75 ppi filter utilized in this work.