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Filtration of dust in an intermittent moving granular bed filter: Performance and modeling

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ABSTRACT

In this work, a new cross-flow intermittent moving granular bed filter was developed and tested. The filter performance was investigated by using airflow at room temperature and under different experimental conditions. The total collection efficiencies obtained were in the range between 82.0% and 99.8%. It was employed different superficial gas velocities, inlet dust concentration and types of dust, with partial substitution of the granular material during the operation in some runs. Macroscopic models to describe the granular filtration based on the assumption of uniform particle deposition were utilized. The characteristic parameters of the filtration were obtained as a function of the average mass specific deposit, expressed as the average relative filter coefficient and the average pressure drop ratio. For the relative pressure drop ratio, the correlation proposed by Ives (1969), resulted in the best curve adjustment. For the relative average filter coefficient, it has been proposed a modified model from Ives (1969) correlation. The filtration parameters presented a dependence on the properties of each particulate employed. These models were used to simulate the filter operation for each experimental run, including the partial granular material substitution cases. The total collection efficiency for different particle size range was determined and used for a prediction test of the average relative filter coefficient.

1. Introduction

Granular bed filters (GBF) are equipments that remove particles from a fluid that pass through a bed. This bed may be constituted of several granular materials. There are four operational modes of GBF: fixed bed, intermittent moving bed, continuous moving bed and fluidized bed [1].

The main characteristic of the GBF's for dust removal are: (i) possibility of removing small size particles (5–10 μm) [2]; (ii) use at high temperatures and pressures [1,3,4]; (iii) dry operation; (iv) simultaneous removal of particulate matter (fly ash) and tar in gasification processes; (v) possibility of using granular material for desulfurization of gases [5,6]; (vi) high efficiency removal of particulate matter [7]; (vii) low pressure drop.

Several technologies were developed for many applications. Equipments for continuous moving bed have been deeply investigated for downstream gas filtration/cleanup in process such as: gasification in combined cycle – gas and steam turbines (IGCC process – Integrated Gasification Combined Cycle System) and in pressurized fluidized bed combustion (PFBC) [5,7–11].

In this work, a new designed GBF proposed by Martins [12] were used. This equipment is classified as a cross-flow intermittent moving granular bed filter. The operation consists in sequential fixed bed mode operations.

The objective of this work is the evaluation of the performance of this new GBF and the determination of models for the average filter coefficient and pressure drop as a function of the specific deposit conditions. These models allow an appropriate scale-up. The experiments were done with air at room temperature. It was employed different superficial gas velocity and particle concentration for two different dust materials. In some experimental runs a partial renewal of the granular material was done. The pressure drop and efficiencies of particle collection were monitored during the operation time, as well as evaluated the particle size distributions of the dust at the effluent.

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Nomenclature

A, B	parameters of the generalized Ergum model (dimensionless)
A_s	parameter used in the effective Stoke number calculation (dimensionless)
C	mass concentration of particles in the gaseous flow (kg m^{-3})
C_{ml}	logarithmic mean of concentrations (kg m^{-3})
c_s	Cunningham correction factor (dimensionless)
d_g	equivalent granular media diameter ≈ Sauter mean diameter (m)
d_P	equivalent granular media diameter (Sauter mean diameter) (m)
E	total collection efficiency (dimensionless)
e	unit collection efficiency; removal efficiency in each unit bed element (dimensionless)
$\overline{F}$	average relative filter coefficient (dimensionless)
$\overline{G}$	average pressure drop ratio (dimensionless)
L	total filter deep (m)
ℓ	length of the periodicity, i.e. thickness of the unit bed element (m)
N	number of unit bed element connected in series (dimensionless)
N_R	interception number (dimensionless)
N_{Re}	Reynolds number (dimensionless)
N_{St}	Stoke number (dimensionless)
$N_{St_{eff}}$	effective Stoke number (dimensionless)
t	time (s)
u_s	superficial gas velocity (m s^{-1})
x	particle volume fraction (dimensionless)
z	axial direction (m)

Greek letters

$\underline{\alpha} = [\alpha_1, \alpha_2, \alpha_3]$	parameter vector of the average relative filter coefficient model (dimensionless)
$\underline{\beta} = [\beta_1, \beta_2, \beta_3]$	parameter vector of the average pressure drop model (dimensionless)
ΔP	pressure drop (Pa)
γ	adhesion probability (dimensionless)
ε	porosity of the filter bed (dimensionless)
η	efficiency of the individual collectors (dimensionless)
λ	filter coefficient (m^{-1})
$\bar{\lambda}$	average filter coefficient (m^{-1})
μ	dynamic viscosity of the fluid (Pa s)
ρ	density of the fluid (kg m^{-3})
ρ_P	density of the particulate matter (kg m^{-3})
σ_m	specific mass deposit on the bed (kg m^{-3})
$\bar{\sigma}_m$	average mass specific deposit (kg m^{-3})

Subscripts

0	indicates the initial state, i.e. the clean filter media conditions
r	denotes the instant of the bed renovation process
$i-j$	indicate that the measure is for particles with sizes between i and j μm
eff	indicate the condition on the effluent of the filter device
in	indicate the condition on the influent of the filter device

2. The cross-flow intermittent moving granular bed filter

Fig. 1 illustrates the GBF used in this work. It consists of a series of six conical louvers plates vertically distributed, with angles of 60° from the horizontal. Similar equipments, but in continuous moving bed, had already been investigated in the literatures [5,7,8,13,14]. The main differences in relation to these equipments are: (i) the position of the louvers; (ii) upstream-louvers are mobile devices fixed on the walls through a shaft.

This filter was designed to make an intermittent operation in the following steps: (i) starting from a clean granular material, the particles in the fluid are deposited along the path as time goes by. The interface is where the most deposition occurs because the inertial impact is the primary removal mechanism in this type of system, according to [1] and [15]. (ii) Thus, there is an increase of the particulate matter deposition, so occurring a continuous increase in the pressure drop through the bed (horizontal plane). (iii) When the pressure drop reaches a pre-defined limit, the mobile louvers are moved to the horizontal position. So, the granular material close to interface that has more quantities of deposited particles, falls into the upstream compartment (see Fig. 1). (iv) Clean granular filter media (that are stored in the upper compartment) slides along the channel in order to occupy the empty spaces. (v) The gas treatment is continuous and the partial renewal of the granular material are made in an intermittently mode, by withdrawing the particles from the dirty interface. Thus, the filter operation becomes a sequence of operations in fixed-bed mode.

3. Theoretical background

3.1. Macroscopic description of granular filtration in fixed-bed mode

Eq. (1) is obtained by applying the material conservation principle in a differential element in a GBF with constant transversal area and homogeneous velocity distribution. In Eq. (1), u_s is the superficial gas velocity, C is the mass concentration of particles in the gaseous flow, z is the axial direction, σ_m is the specific mass deposit, and t is the time.

$$u_s \frac{\partial C}{\partial z} + \frac{\partial \sigma_m}{\partial t} = 0 \tag{1}$$

According to Tien and Ramarao [16], the filtration rate can be expressed by a first order law, according to Eq. (2). The parameter λ is known as the filter coefficient.

$$\frac{\partial C}{\partial z} = -\lambda C \tag{2}$$

The filter coefficient can vary in the axial direction, as reported by Walata et al. [17]. However, if assuming uniform particle deposition, and by combination of Eqs. (1) and (2), Eq. (3) can be obtained. In this expression, the local mass specific deposit, σ_m was replaced by an average mass specific deposit, $\bar{\sigma}_m$, between the inlet and the outlet of the bed. In this way, the filter coefficient is expressed as an average filter coefficient, $\bar{\lambda}$, as well as the concentration is now expressed as a logarithmic mean concentration, C_{ml}.

$$\frac{\partial \bar{\sigma}_m}{\partial t} = u_s C_{ml} \lambda_0 \overline{F} \tag{3}$$

The average filter coefficient $\bar{\lambda}$, is formulated as $\overline{F}$ function, defined as a ratio of current and initial filter coefficient, λ_0, according to Eq. (4). The average filter coefficient ratio, $\overline{F}$ (or relative filter coefficient), varies with time and suggest, according to Tien and Ramarao [16], a function of the specific deposit, $f(\underline{\alpha}, \bar{\sigma}_m)$, were $\underline{\alpha}$ is the parameter vector of the model. The form and parameters value of the model depends on the filter to be used and the suspension to be filtered.