SCALED STUDY ON GRANULAR FILTRATION FOR AIR POLLUTION CONTROL

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Abstract. *This paper reviews the issues of similarity and the relevant dimensionless parameters for scaled studies on granular filtration for air pollution control and applies a methodology to analyze the theoretical performance of a granular filter under development. Significant reduction of exposure to air pollution can be achieved through lowering the concentrations of several of the most common air pollutants emitted during the combustion of fossil fuels. Most industrial activities tend to adhere to end-of-pipe control devices. Granular filtration is suitable in treating high-temperature and/or corrosion gaseous streams. Five dimensionless parameters represent a complete set of independent variables describing the behavior of a moving bed granular filter: Stokes number, Reynolds number, interception number, density ratio, and Froude number. The analysis indicates that the filter under development theoretically would have good collection efficiency, and that there is room for its improvement.*

Keywords*: air pollution control engineering, granular filtration, physical modeling*

1. INTRODUCTION

In engineering, problems are approached in an analytical, numerical and/or experimental manner. Mathematical models make the analysis relatively faster and cheaper and computational fluid mechanics resolves virtually diverse problems. If there is no model available or there is not a representative and validated model of the phenomenon at study, physical modeling is the alternative (Maliska, 2004). The experimental approach is the conservative one: phenomenon investigation should start experimentally, in order to gain insight of its governing laws and mathematical relations. The experiment may be designed in real size or in reduced or enlarged scale (Sedov, 1993).

In the study of air pollution control equipment, reduced-scale experiments are interesting as the reduced space is better controlled, which turns possible the creation of scenarios. Data is later transposed by the scale relation to describe the phenomenon in real size. In order for this description to be valid, similarity between the two sizes must be kept (Walker, 2006).

This paper reviews the issues of similarity and the relevant dimensionless parameters for scaled studies on granular filtration for air pollution control.

2. FUNDAMENTALS

2.1. Air pollution control

Air pollution is a major environmental risk to health and is estimated to cause approximately two million premature deaths worldwide per year. Pollutants of major public health concern include particulate matter, carbon monoxide, ozone, nitrogen dioxide and sulfur dioxide. Exposure to air pollutants is largely beyond the control of individuals and requires action by public authorities at the national, regional and even international levels (World Health Organization, 2008).

In conventional air pollution control, established engineering methods are applied to mitigate air pollution. A typical air pollution problem can be resolved through one of the following mitigation options: enhancing dispersion, adopting pollution prevention by process change, and using end-of-pipe control device. Most industrial activities tend to adhere to the last option, removing or destroying sufficient contaminants from the gas stream through chemical or mechanical processes that the final discharge into the ambient air is below an acceptable threshold (Tiwary and Colls, 2010). Common equipment are cyclones, bag filters, electrostatic precipitators, and wet scrubbers (Braga *et al.*, 2005).

2.2. Granular filtration

Granular filtration is a fluid-solid separation process commonly applied to remove minute quantities of small particles from various kinds of fluids. Either liquid or gas fluid streams can be treated. The basic principle of granular filtration remains the same regardless of the system being treated, the medium used, or the manner in which filtration is conducted. The suspension is made to pass through a medium composed of granular substances (granular medium) under pressure or gravity. As the suspension flows through the medium, some of the particles present in the suspension, because of the various forces acting on them, move toward and become deposited on the surface of the granules of which the medium is composed. The extent of deposition throughout the medium, in general, cannot be made uniform. However, the entire medium is intended to be used for particle collection (Tien and Ramarao, 2007).

Because of the relative abundance of granular substance which are resistant to temperature and corrosion, granular filtration is more suitable in treating high-temperature and/or corrosion gaseous streams (Tien and Ramarao, 2007). Together with ceramic candle filters, granular bed filters are the most promising approaches to hot gas clean-up for advanced coal conversion technologies. Granular bed filters are more attractive because they employ low-cost filter media and offer the prospect for constant pressure drop if the filter is operated as a moving bed (Smid *et al.*, 2004). In moving bed cross-flow operations, the filter bed is a vertical layer of granular material held in place by retaining grids or louvered walls. The filter granules move downwards and are removed from the bottom of the moving bed filter, while the gas passes horizontally through the granular layer. The filter media must be kept in uniform flow conditions without stagnant zones inside the bed in order not to be plugged in the moving granular bed filter (Hsiau et al., 2008).

Granular filtration may also be conducted in fixed-bed or fluidized-bed mode, but they have some disadvantages. The conventional technology of fixed bed suffers from a major disadvantage that the gas flow must be stopped for cleaning. The fluidized bed is continuous in operation but is less effective in removing small particulates than a fixed or dense packed moving bed. Furthermore, it requires a substantially uniform flow of gas. More particularly, any sudden surge of gas going through the fluidized bed can result in not only the previously contained particulates passing through the bed but also a portion of the bed itself being entrained in the gas, thus adding even more to the particulate loading of the gas stream (Hsiau *et al.*, 2008).

2.3. Modelling and the similarity theory

The concept of modeling according to Sedov (1993) is the substitution of a phenomenon investigation in natural conditions (prototype) for the investigation of a scaled similar phenomenon under defined conditions (model). Two phenomena are similar if from one's characteristics it is possible to gain insight of other's by transposition using a scale relation. These characteristics are relations between the relevant variables of the phenomenon, deduced by dimensional analysis, generating dimensionless parameters. This analysis can be done by Buckingham Pi theorem, by problem's physical analysis and by the analysis of the governing equations, dividing the variables by their respective references (Gulliver, 2007). This makes possible the identification of the dominant forces (Fox *et al.*, 2006). Identified the relevant parameters, empirical relations may be established between them, generating curves with similar shapes that theoretically may also be used in the study of other similar phenomena—similarity theory (Stull, 1988). The necessary and sufficient condition in order for two phenomena to be similar is the numerical values of the relevant dimensionless parameters to be constant—similarity criterion (Sedov, 1993).

Modeling based on similarity theory became known with Reynolds work in hydraulics, published in 1883 (Sedov, 1993). The Reynolds number, that relates inertial and viscous forces, became the most known and useful dimensionless parameter of fluid mechanics (Ting, 2005). In air quality and atmospheric pollution simulation, physical modeling began in the 70s, with wind tunnel and water tank studies (Wittwer, 2006). Common working fluids are air, water and salt water mixtures. Scales are generally defined by the availability of space and instrumentation for the experiment (Walker, 2006).

The similarity criterion guarantees the similarity conditions that must be kept in order for the scaled model to describe correctly the real size prototype: geometric similarity (shapes), kinetic similarity (velocities) and dynamic similarity (forces). Kinetic similarity requires geometric similarity, and dynamic similarity requires kinetic similarity, but is only ensured if numerical values of the phenomenon relevant dimensionless parameters are constant between model and prototype (Fox *et al.*, 2006). Complete similarity is guaranteed, therefore, if model and prototype are geometrically similar and the dimensionless parameters are the same for both (Ting, 2005).

3. SCALED STUDY DESIGN

3.1. Geometric similarity

Geometric similarity is theoretically the simplest condition to be kept between model and prototype: defined the reduction scale (1:*e*), all prototype linear dimensions must be divided by the scale's numerical value (*e*) to get model dimensions (Fig. 1). All dimensions must be proportionally reduced at three axis by the same factor: the ratio of all lengths of any sequential design to all the lengths of the basic design must be constant (Pahl *et al.*, 2007).

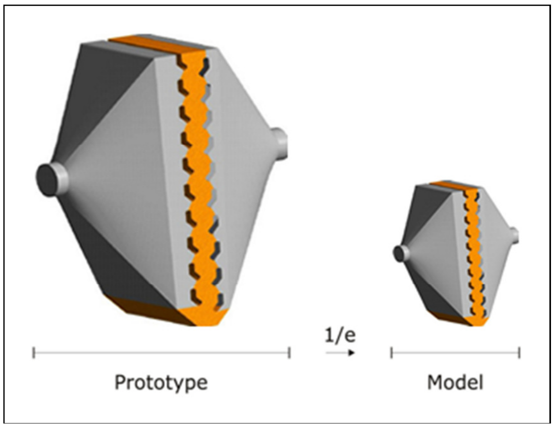

Figure 1. Geometric similarity

All dimensions must be proportionally reduced by the same factor, including the diameter of the granules of the granular medium. Geometric similarity is achieved by fixing the ratio of characteristic filter dimension, such as filter diameter (D) and granule diameter (d_g). This dimensionless size ratio is designated as L (Brown *et al.*, 2003):

$$L = D/d_g \tag{1}$$

3.2. Relevant dimensionless parameters

Shi (2002) examined the performance of a moving bed granular filter under conditions simulating hydrodynamic flow at high temperature, high pressure typical of advanced coal-fired power systems through a cold-flow model of a moving bed granular filter. Typical hot gas clean-up for advanced coal power systems operates at temperature around 850 °C and pressure on the order of 10 atmospheres, and such running conditions are not easily achieved with laboratory experiments. Similitude analysis was used to design experiments so that they could be performed at near-ambient conditions while preserving hydrodynamic flow properties typical of hot gas filtration. It was concluded that five dimensionless parameters represent a complete set of independent variables describing the behavior of a moving bed granular filter: Stokes number, Reynolds number, interception number, density ratio, and Froude number (Brown *et al.*, 2003).

- The Stokes number controls the collection mechanism of granular filters operating in the inertial impaction regime:

$$St = \frac{\rho_p d_p^2 U C_S}{9\mu d_g} \tag{2}$$

where ρ_p is the dust particle density, d_p is the dust particle diameter, U is the superficial velocity at the face of the filter media, C_s is the Cunningham's correction factor for molecular slip, μ is the fluid viscosity and d_g is the granule diameter. Generally, the collection efficiency exceeds 90% for a granular bed when $St > 0.01$, which corresponds to particles larger than a few microns.

- The Reynolds number based on granular diameter expresses the hydrodynamic similarity:

$$Re = \frac{\rho_f U d_g}{\mu} \tag{3}$$

where ρ_f is the density of the fluid (gas).

- The interception number, together with the Stokes number, expresses the particle trajectory similarity under conditions of inertial impaction:

$$R = \frac{d_p}{d_g} \tag{4}$$

- The density ratio describes the hydrodynamics of the moving bed:

$$P = \frac{\rho_g}{\rho_f} \tag{5}$$

where ρ_g is the density of the granule.

- The Froude number also describes the hydrodynamics of the moving bed:

$$Fr = \frac{U^2}{g d_g} \tag{6}$$

where g is the acceleration due to gravity.

Thus, the efficiency of a moving bed granular filter can be described by a relationship of the form $\eta = f(St, Re, R, P, Fr)$, where first three parameters express the efficiency of an inertial impaction filter and the other two express the hydrodynamics of the moving bed. For two moving bed granular filters operating in the inertial impaction regime, the particle collection efficiency and dimensionless pressure drop of these filters will be identical if these five dimensionless parameters and the size ratio L are equal. Complete similarity is achieved by satisfying the following relationships referring to prototype/model gas, dust particles and bed granules densities (Brown *et al.*, 2003, Shi, 2002):

$$\frac{\rho_{p1}}{\rho_{p2}} = \frac{\rho_{g1}}{\rho_{g2}} = \frac{\rho_{f1}}{\rho_{f2}} \tag{7}$$

$$\frac{U_1}{U_2} = \left(\frac{\upsilon_1}{\upsilon_2}\right)^{1/3} \tag{8}$$

$$\frac{D_1}{D_2} = \frac{d_{p1}}{d_{p2}} = \frac{d_{g1}}{d_{g2}} = \left(\frac{\upsilon_1}{\upsilon_2}\right)^{2/3} \tag{9}$$

where υ is the kinematic viscosity of the fluid, $\upsilon = \mu/\rho_f$.

4. GRANULAR FILTERS FOR COAL-FIRED POWER PLANTS: CASE STUDY

Significant reduction of exposure to air pollution can be achieved through lowering the concentrations of several of the most common air pollutants emitted during the combustion of fossil fuels. Such measures would also reduce greenhouse gases and contribute to the mitigation of global warming (World Health Organization, 2008). Almost all fossil fuels use is by burning them to produce energy, which is basic for life and activities in society. Attempts to restrict the use of fossil fuels for environmental reasons are likely to have a negative impact on economic development and the overall availability of energy (New Energy Alternative, 2008, 2009).

Coal is the most abundant and economical of fossil fuels. It plays a central role in supporting global economic development, alleviating poverty and is an essential resource to meeting the world's energy needs. Coal currently supplies 27% of primary energy and 41% of electricity generation. Its use is forecast to rise over 50% to 2030, with developing countries responsible for 97% of this increase, primarily to meet electrification rates (World Coal Association, 2011).

Brazilian mineral coal reserves are estimated at approximately 32 billion tons. Coal is the largest national non-renewable energy source, representing 46% of Brazilian fossil fuel reserves. Reserves are located in the south of Brazil, in the states of Paraná, Santa Catarina and Rio Grande do Sul. It is used in generating electric power, in the metallurgic industry, for producing metallurgic coke and for generating heat for various industries, the chemical, cement, paper, ceramic and metal industries in particular. The generation of electric power provides the largest market for national coal, 87.6%. Coal as an input for generating electric power began with the diversification of the electrical sector's energy matrix, in order to reduce the vulnerability of hydroelectric systems and contributed to optimizing energy supply (Sindicato da Indústria da Extração de Carvão do Estado de Santa Catarina, 2006).

Aiming to support the coal productive chain in order to encourage its sustainable use, in 2007 a group of researchers formed "Rede Carvão", the Brazilian Mineral Coal Research, Development and Innovation Network. Funded by the Brazilian Ministry of Science and Technology, it supports projects on coal production, conversion and applications, and environmental issues (Rede de Pesquisa, Desenvolvimento e Inovação do Carvão Mineral, 2010). One of the environmental issues related to coal energy generation is air pollution, which is mitigated by the use of end-of-pipe control devices, mainly bag filters for removal of suspended particulates from gas stream followed by wet scrubbers for its desulfurization. Rede Carvão is funding the development of a granular filter capable of both particulate removal and desulfurization. Figure 2 shows the project prototype. Current development stage is a fixed 2 mm glass beads bed. Pressure drop tests at the recommended superficial velocity of 0.2 m/s indicate values around mmWC (~490 Pa).

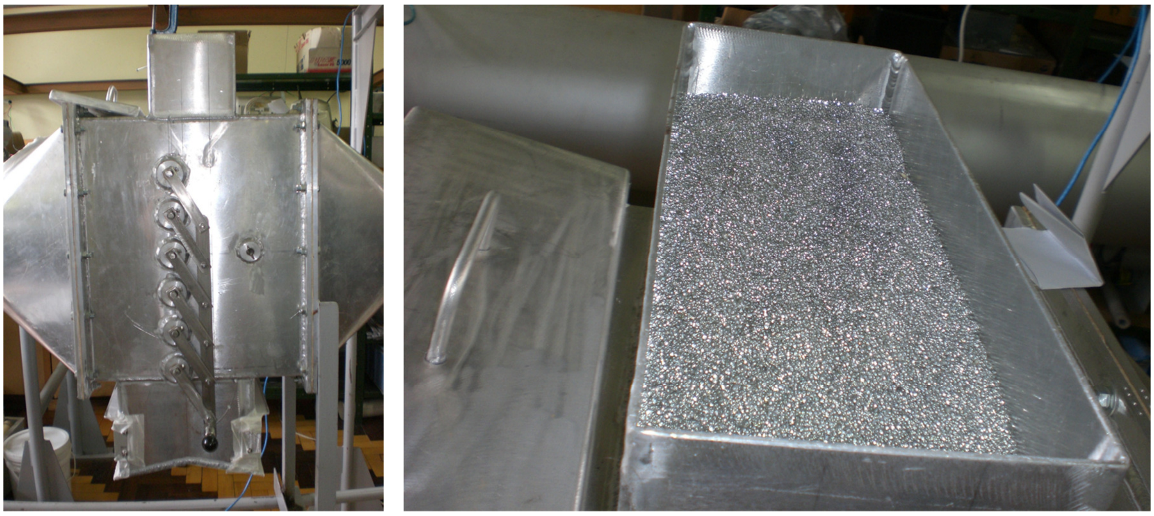

Figure 2. Project prototype: filter (left) and granular medium (right)

In advanced coal-fire cycles it is important to remove the fine particles from high temperature and high pressure gas streams, to satisfy gas turbine fuel quality requirements. Hot gas clean-up's major benefit is seen in higher system efficiencies resulting from retention and utilization of the sensible heat in product gases. Current integrated gasification combined cycle systems (IGCC) remove particulates by condensing or quenching the raw fuel gas with water (wet scrubbing), and pressurized fluidized bed combustion designs (PFBC) employ cyclone (inertial) separators upstream of the gas turbine in conjunction with an electrostatic precipitator or fabric filter downstream of the gas turbine. Advanced IGCC and PFBC systems employ rigid, porous (typically ceramic) barrier filters that operate at high temperature (480 °C to 980 °C) and pressure (Smid *et al.*, 2004). A typical moving bed granular filter operates at 850 °C and 1000 kPa absolute, under which, the air density is about 3.10 kg/m^3 (Shi, 2002). Assuming these conditions and the similitude factors examined by Shi (2002), the filter under development (cold-flow model) would represent the hot-flow conditions shown in Tab. 1.

According to Brown *et al.* (2003), generally, the collection efficiency exceeds 90% for a granular bed when $St > 0.01$, which corresponds to particles larger than a few microns. Thus, the filter under development theoretically would have good collection efficiency.

At the experiment of Shi (2002), the test with 4 mm granules had higher efficiency than the test with 2 mm granules, under the same hydrodynamic conditions. It was concluded that this type of moving bed filter is robust with high efficiency when 4 mm granules are used as the filtration media and the superficial velocity is 0.2 m/s under similar conditions. The filter under development is currently using 2 mm glass beads as bed. Thus there is room for improvement in its collection efficiency.

Table 1. Properties for cold-flow model and hot-flow prototype filters

Property	Model	Prototype	Factor
Gas pressure (kPa)	159.67	897.35	5.62
Gas temperature (^oC)	21.00	892.50	42.50
Gas density (kg/m^3)	3.10	3.10	1.00
Gas viscosity (kg/ms)	1.74E-05	4.26E-05	2.45
Ash particle diameter (μm)	2.75	5.01	1.82
Ash particle density (kg/m^3)	2350.00	2350.00	1.00
Granule density (kg/m^3)	2450.00	2450.00	1.00
Granule diameter (mm)	2.00	3.66	1.83
Filter diameter (m)	0.10	0.18	1.83
Superficial velocity (m/s)	0.21	0.28	1.35
St	0.01	0.01	
Re	75	75	
R	0.0014	0.0014	
P	790	790	
Fr	2.2	2.2	
L	50	50	

5. CONCLUSION

Issues of similarity and the relevant dimensionless parameters for scaled studies on granular filtration for air pollution control were reviewed and a methodology was applied to analyze the theoretical performance of a granular filter under development. Five dimensionless parameters represent a complete set of independent variables describing the behavior of a moving bed granular filter: Stokes number, Reynolds number, interception number, density ratio, and Froude number. The analysis indicates that the filter under development theoretically would have good collection efficiency, and that there is room for its improvement.

6. ACKNOWLEDGEMENTS

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