XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

EFFECT OF SEDIMENTATION ON MODELING COMPRESSIBLE CAKE FORMATION IN GAS FILTERS

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Abstract
Gas flow through the cake formed over the surface of a gas filter creates an aerodynamic drag that increases mechanical compression on the layers closer to the surface, reducing their thickness and permeability. This induces an increase of the pressure drop through the filter-cake system compared to the incompressible cake case. Part of the particles from the incoming gas stream settles down in the filtration vessel and do not participate on cake formation. A model was developed, taking into account cake compressibility, to check the effect of the settling process. Darcy's Law was used to calculate the pressure drop through each layer of filter cake. Three constant velocity laboratory filtration experiments under high temperature coal gasification conditions were used to determine the empirical parameters required, as well as to validate the model. It was observed that the precision of the model in predicting the filter cleaning intervals depends on the knowledge of the settling process.

Keywords: *Gas filtration, Cake compressibility,Cleaning interval.*

1. INTRODUCTION

Surface filtration may be used for hot and cold gas cleaning when highly pure gas is needed. The particulate-laden gas stream is forced through a surface with small size pores, so that a cake is formed over it, and where most of the filtration takes place. The filters are periodically cleaned on-line by a backpulse of pressurised gas, causing a short reverse flow that displaces the cake from its surface. The detached cake falls and is collected into the filtration vessel hopper.

Applications of high temperature filtration are being developed to protect downstream equipment, such as gas turbines in power generation, when burning coal; to recover valuable particulate, such as FCC (Fluid Cracking Catalyst) in oil refineries, and to meet environmental standards.

This work considers the rise with time of the pressure drop in the cake due to the build - up of its thickness and change of its properties during operation. When the filter is conditioned, after each cleaning pulse the pressure loss returns to the same baseline value, so that a steady filtering cycling process is established, as seen on Fig. 1.

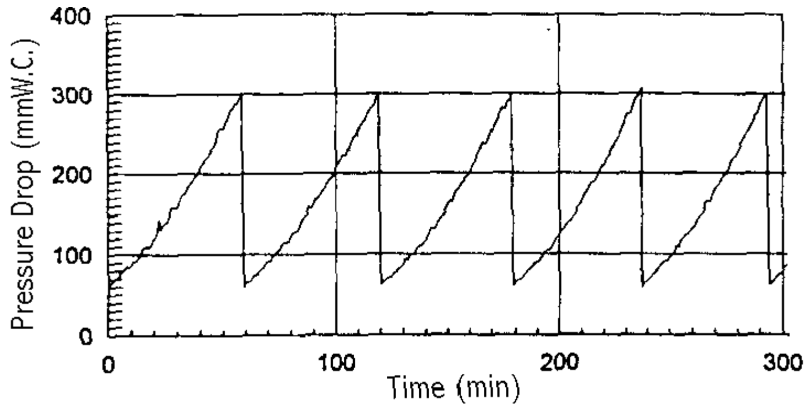

Figure 1. Typical pressure drop experimental curve

The compressibility of the cake may be explained by two factors: the compressibility of the particles themselves and their re-arrangement. Collisions and interparticle forces allow the formation of agglomerates in the gas stream. These flying structures plus the free flying particles form the dust cake when reaching the solid filtering surface. The final structure of a recently formed cake is made up by these airborne chains, rearranged or broken after impact, and the bigger flying particles. This layer retains most of the smaller particles. New agglomerates are also formed, depending on the material and process conditions. When the next layer is formed over, the compression caused by its aerodynamic drag increases the local pressure. Some of the structural members (such as bridges, arches or columns) do not support the increased stress and collapse. This reduces the layer's thickness, porosity and permeability. Particle migration and cake structure settling occurs simultaneously and interactively, and the process is more intense closer to the cake-gas interface. The whole system behaviour depends on the possible phenomena combinations.

Most models of cake filtration are based on packed-bed flow equations, that consider an assemblage of particles from the gas stream (Happel and Brenner, 1986, Theilander and Fathi-Najafi, 1996, Endo *et al.*, 1998, Schmidt, 1997). Particle mean diameter, sphericity and size distribution are used as if the bed (or cake) was formed by well-behaved geometric arrays of these particles. Nonetheless, Alvin (1995) reported rod-like formations and plate-like formation in the microphotography analysis of dust cakes, as well as other combinations, what leads to the conclusion that most cell models are only rough approximations of reality. Models also do not consider that part of the particles from the incoming gas stream settles down in the filtration vessel and do not participate on cake formation. The present work proposes a model to take into account these phenomena and check the effect of the settling process on the filtration process.

2. MODEL DESCRIPTION

The filter cake build-up is schematically depicted on Fig. 2. It was assumed that the gas velocity was constant, each layer was formed during equal time intervals, and the gas carries particles (with volume concentration c) that travel with the same velocity until the solid filter or cake surface was reached. It was assumed that any recently formed layer had the same characteristics of the first one reaching the filter surface. When new layers were formed, only the layer closer to the filter surface would be under new conditions, while the others assumed the condition of their older adjacent layer. So, when another layer was formed, the calculations of flow resistance and pressure drop were made only for layer A, that is, the layer closer to the surface.

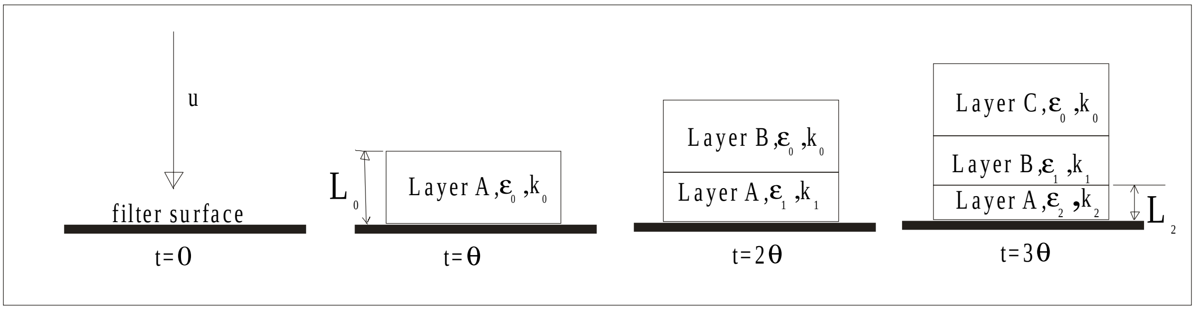

Figure 2. Schematic representation of the cake formation model

Darcy's Law was used to find the pressure loss on each layer, building-up the history of a filter cake according to the gas flow face velocity (u) and dynamic viscosity (μ), and layer thickness (L_i):

$$\Delta P_i = \left(\frac{1}{k_i}\right)\mu L_i u \quad (1)$$

where k_i is the permeability of the layer.

The Carman-Kozeny equation and the Happel cell model could also have been used to calculate the pressure drop instead of Darcy's. They both rely on the particles mean diameter (Dp) and sphericity (φ). The mean diameter, nonetheless, does not represent reality, where there is a size distribution, and the structure of the cake is formed by arrangement of agglomerates and structural members, as reported by Alvin (1995). Neiva et al. (1999) showed comparatively the advantage of applying Darcy's law, as it worked directly with the compressibility effects on the pressure drop, dispensing the need of assumptions concerning the particle characteristics to calculate the permeability.

Considering continuity, the volume of solids per unit area W [m_s^3/m^2] of dust cake formed during a time interval θ [s] is given by:

$$W = \lambda c u \theta \quad (2)$$

where c is the volumetric concentration of the incoming gas stream [m_s^3/ m_g^3] and λ is the settling factor [dimentionless]. The volumetric concentration of the gas arriving on the cake surface is smaller than the volumetric concentration of the incoming gas stream (c), because part of the particles in the gas stream that entered the filtration vessel falls down in the bottom of the vessel, before reaching the filtration surface. The settling process is caused by an increase of the cross section area and/or impact against eventually existing distribution baffles, so (λc) represents the portion of the particles that actually participate on cake formation.

The thickness (L_i) of a layer may be written as:

$$L_i = \frac{W}{1-\varepsilon_i} = \frac{\lambda c u \theta}{1-\varepsilon_i} \tag{3}$$

where ε_i is the layer porosity. Defining α_i as a modified specific cake resistance,

$$\alpha_i = \frac{1}{k_i(1-\varepsilon_i)} \tag{4}$$

the pressure loss calculated by Darcy's law may be rewritten as:

$$\Delta P_i = \alpha_i \lambda c \theta \mu u^2 \tag{5}$$

An empirical constitutive equation proposed by Stamatakis and Tien, in 1991, was adopted to calculate the effect of pressure on the specific resistance of a given layer:

$$\alpha_i = \alpha_0 \left[1 + \frac{\left(\sum_{j=1}^{i-1} \Delta P_j \right)}{P_A} \right]^{\gamma} \tag{6}$$

where the index *i* refers to the *i*th layer, α_i is the resistance of the layer to be determined, α_0 is the initial resistance, that is, the resistance attributed to every newly formed layer; $\sum_{j=1}^{i-1} \Delta P_j$ is the total pressure drop caused by the external layers over the ith layer, and γ and P_A are empirical parameters. α_0 , γ and P_A are dependent on the materials and process conditions, and must be determined by adjustment of the model to experimental data.

For a given time interval θ, the pressure drop of the first layer may be determined by Eq. (5) if parameters α_0 , γ and $P_{A,}$ and the process conditions are known. This enables the calculation of the pressure drop of the following layers, resulting in a curve as shown on Fig. 1.

3. PARAMETERS DETERMINATION

Although a rather large number of filtration experiments was published, there is a lack of criteriously measured pressure drop data where the compressibility effects can be perceived. In some of the experiments by Ergündler et al. (1997) – constant velocity laboratory tests, under coal gasification conditions at 550 ^{0}C – the compressibility effect can be clearly seen, as was shown on Fig. 1, where the rise of the pressure drop with time does not happen according to a straight line, as when no compressibility occurs, but slightly curved upwards, which means that the specific flow resistance increased with time.

The experimental filtration vessel is shown on Fig. 3. Three ceramic textile candles were used, and the cleaning pulse was applied simultaneously when a maximum set-up pressure drop was attained.

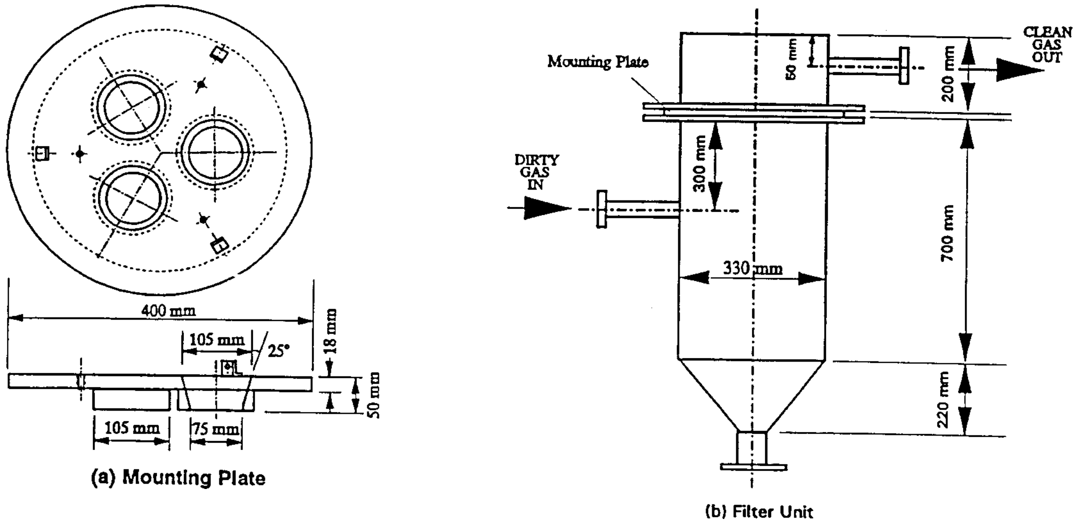

Figure 3 – Experimental filtration vessel used by Ergündler *et al.*(1997)

As may be observed, there is an increase of the cross sectional area when the particle ladden gas enters the filtration unit, causing a reduction of the air velocity, that induces a fraction of the particles to settle down in the filtration vessel hopper, other than participating on cake formation. The settling factor λ was introduced in the model equations to enable an analysis of its influence. It depends, in general, on the geometry of the filter vessel and process conditions, such as velocity, gas viscosity, concentration, density, particle size and agglomerates formation. Another agent that influences cake formation is the particle static charge. Although it is difficult to quantify this effect, if the static charges in the experiments are of the same magnitude as those in industrial filtration systems, no significative difference should occur. The neutralisation of the electric charge in the experiments is possible, and was done by Schmidt (1995) and Dittler *et al.* (1998). The results obtained were independent of electric charges, but were clearly different from the industrial process where these charges are present. Ergündler *et al.* (1997) provided a roughly estimated λ value, by assuming a condition of constant porosity throughout the cake, and found that higher face velocities increased the factor.

The empirical coefficients α_0, γ and P_A, which allow correlating the pressure drop *with* time, $\Delta P^M = \Delta P^M(t)$, for a given set of process conditions, were obtained in this work from Ergündler's experimental curves $\Delta P^E = \Delta P^E(t)$, by minimization of an objective function, $f(\alpha_0, \gamma, P_A)$, defined as (Stamatakis and Tien, 1991):

$$f(\alpha_0, \gamma, P_A) = \sum_{j=1}^{n} \left(\frac{\Delta P_j^E - \Delta P_j^M}{\Delta P_j^E} \right)^2 \tag{7}$$

where the index *j* refers to the *j*th point; i.e. values at t_j.

Figure 4 shows that this function attains a minimum P_A value when the other two coefficients were maintained fixed, and therefore $f(\alpha_0=\text{const.}, \gamma=\text{const.}, P_A)$ was convex. The same happened when the variable was α_0 or γ. The numerical determination of the minimal of this function started with an initial value for the three parameters, and was carried out by optimizing one parameter at a time.

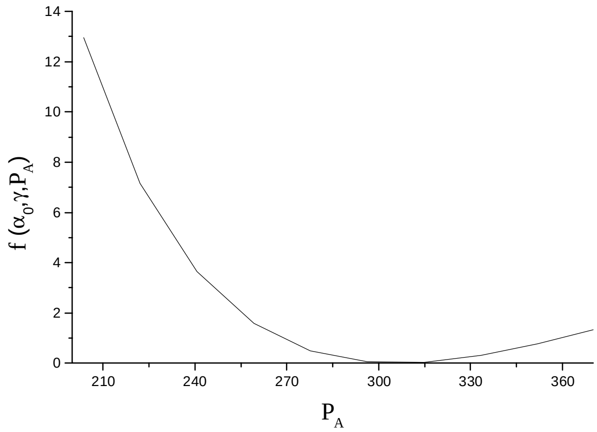

Figure 4. Typical objective function (f) behaviour

If γ, for instance, was the parameter to be optimized, the function f was calculated for f (α_0, γ, P_A), f (α_0, γ+h, P_A) and f (α_0, γ-h, P_A), where h was a chosen step. The three values obtained for f were supposed to be points of a parabola, whose minimum was determined. This point was used as the second approximation for γ. This procedure was repeated until a relative reduction of the function was attained. Afterwards the program proceeded to optimize the second and third variables, where the iterative process was repeated, and then back to the first one again. Everytime a new value of f was calculated it was checked against a chosen tolerance, that was the halting criteria. The assumption of the initial values for α_0, γ and P_A in each experiment constituted a critical step. As the optimization procedure was carried out, the function f was calculated several thousands times for each run. The fitted curves matched the experimental data with good approximation, the values of f (α_0, γ, P_A) being under 10^{-2}. The results for λ=1 (no settling assumed) are shown on Table 1.

Table 1 - Fitted parameters - No settling

Experiment	A	B	C
Face Velocity u (m/s)	0.012	0.012	0.016
Filtration Period (min)	130	160	58
α_0	4.00E+11	8.05E+11	8.30E+11
γ	0.457	0.43	0.45
P_A	114	580	210

where **e**xperiments A, B and C correspond to the experiments shown on Figs. 6a, 7a and 7b in Ergündler et al. (1997).

The sensivity of the model to the three empirical parameters was evaluated, and it was found that P_A had a smaller influence than α_0 or γ.

Simulations were made considering several settling factors, including Ergündler's (1997) calculated values, (λ_A=0.42, λ_B=0.61 and λ_C=0.98), which gave better approximation to the experimental results than λ=1. They estimated these values from the cake thickness, calculated with the Carman-Kozeny equation, assuming that the cake had constant properties along it's depth, and took porosity as ε=0.72 for all cases. So far there are no experiments in which λ was effectively determined. In the absence of such information, several settling factors were assumed and tested, and the set (λ_A=0.50, λ_B=0.65 and λ_C=0.95) best approximated the model to experimental results. The fitted parameters found on applying the estimated λ values are shown on Table 2. As it may be observed, the settling factor affects mostly α_0 , γ to a lesser extent, and has almost no influence on P_A.

Table 2. Fitted parameters - Best estimated settling factor

Experiment	A		B		C	
	Ergündler	This Work	Ergündler	This Work	Ergündler	This Work
λ	0.42	0.50	0.61	0.65	0.98	0.95
α_0	9.50E+11	8.01E+11	1.30E+12	1.22E+12	8.30E+11	8.60E+11
γ	0.474	0.470	0.457	0.457	0.467	0.463
P_A	121	121	590	590	210	210

4. MODEL VALIDATION

Model validation for experimental test A, was made using as parameters the average of the parameters fitted to experiments B and C. Analogous procedure was carried out to check the model in experiments B and C. The average parameters applied to the model are shown on Table 3.

Table 3. Average parameters used for validation

Experiment	A			B			C		
$\lambda_{Obs.}$	1.00_I	0.42_{II}	0.50_{III}	1.00_I	0.61_{II}	0.65_{III}	1.00_I	0.98_{II}	0.95_{III}
α_0 (xE11)	8.17	10.6	10.4	6.15	8.90	8.31	6.03	11.2	10.1
γ	0.44	0.46	0.460	0.45	0.47	0.47	0.44	0.47	0.46
P_A	395	400	400	162	166	166	347	356	356

Obs. I- No settling, II - Ergündler et al. (1997), III - Present work.

Comparison of the experimental measured pressure drop ($\Delta P^E = \Delta P^E$ (t)) with the model, for these settling factors, is shown on Figs. 5, 6 and 7.

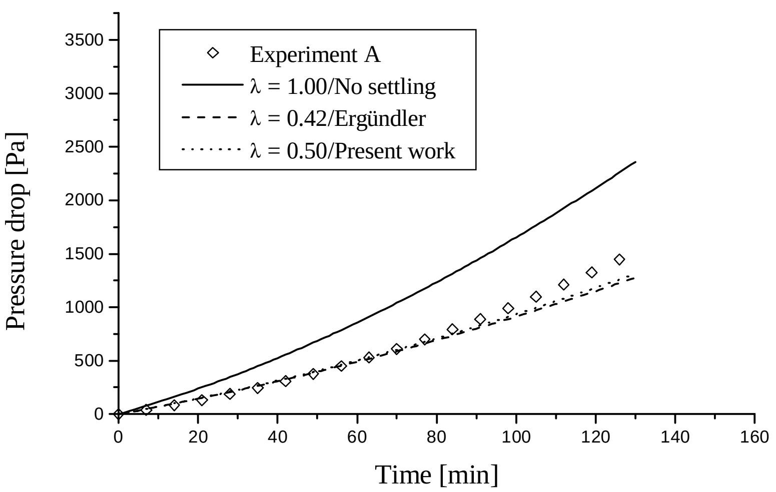

Figure 5. Model validation for experiment A

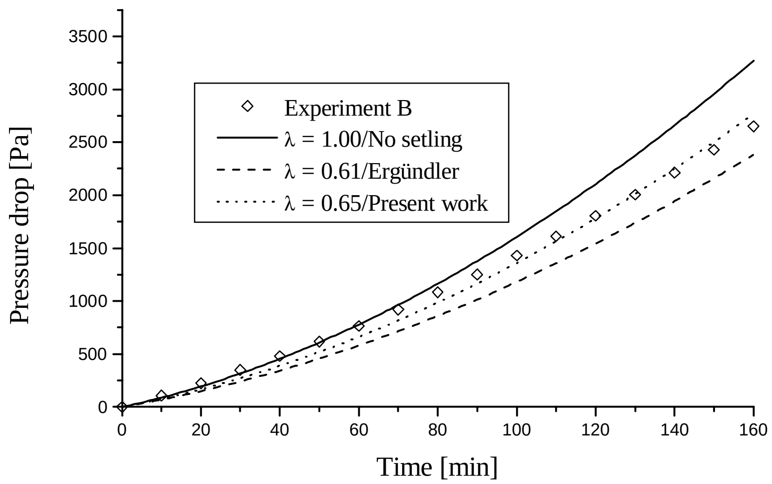

Figure 6. Model validation for experiment B

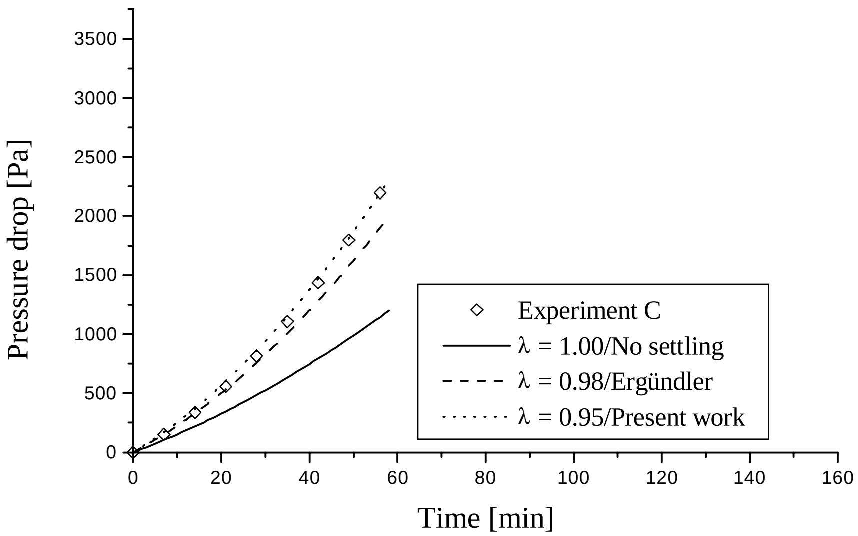

Figure 7. Model validation for experiment C

It can be seen that the assumption of a settling factor in the model can bring the results closer to the experimental values in all three cases. Ergündler's procedure provided a reasonable estimate of the evolution of pressure drop with time. The present model, which takes cake compressibility into account, made possible, by trial and error, a closer approximation, but this fact only reafirms the importance of the settling phenomenon, and the need of its systematic study. Analysis of Fig. 6 (experiment B), for example, shows that the calculated filtration period corresponding to the build-up of a maximum filter pressure drop of 2400 Pa, varied from 18 min less than the experimental data, in Ergündler's work, to 12 min longer, when no settling was assumed. To these correspond relative errors in the range from -12% to +8%, respectively.

5. CONCLUSIONS

A simulation model was developed to calculate the pressure drop build-up during compressible cake formation in a constant velocity filtration system. Darcy's Law was used to calculate the pressure drop through each layer of filter cake. Three laboratory filtration experiments under high temperature coal gasification conditions were used to determine the empirical parameters required, and to verify the model. Part of the particles from the incoming gas stream settles down in the filtration vessel and do not participate on cake formation. The model developed allowed checking the effect of the settling process. An uncertainty on the prediction of the cleaning intervals of the order of 12 percent was found, for the range of process conditions of the experiments here considered.

The design of a filter vessel should promote settling of the dust into the hopper, to reduce cake build-up, saving compressed cleaning gas and increasing the filter candles life, due to longer operating intervals before cleaning is required. As settling always will always occur on industrial systems, knowledge of its behavior must be available as a prerequisite to simulate the filter pressure drop build-up story.

As a suggestion, the following themes should be further explored:

- Measurements of the settling factor;
- Study of the effects of the interparticle forces on agglomerate formation, both on the air stream and in the cake, as requisites for reliable modeling.

Acknowledgements

The first author wishes to express his gratitude to the ALFA Program, supported by the European Commission, and to Professor Jesus Arauzo, of UNIZAR – University of Zaragoza, Spain.

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