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Optimal design of a settling chamber – an air pollution control device

R.C. Bhattacharjee
Department of Civil Engineering
National Institute of Technology
India

Abstract

Various industries release dust and smoke to the atmosphere causing air pollution problems. Settling chambers are the devices that are introduced to the industrial exhaust system to remove solid particles from the emission. The particles while passing through the chamber, settle over the settling trays under the action of gravity, thus cleaning the gas. These chambers can collect reasonably small particles with excellent reliability. The design of such structures involves a three-fold problem – it should be functionally efficient, structurally safe during use, and its cost should be minimum. The present status of design of these devices is limited to their fluid dynamic design only based on the particle settling principle with little attention paid to the structural safety and minimization of cost. Presented herein is a methodology for optimal design of a settling chamber satisfying all the above criteria, i.e. fluid dynamic requirements, structural safety conditions, and minimization of cost.

Introduction

In various industrial processes, large amount of dust is generated. The quantity of dust that can be released to the atmosphere, is limited by the emission standards. To maintain emission levels within prescribed limit, air pollution control devices are inserted into the flow system. Settling chamber is one of such devices that removes particles from industrial emission. It can effectively collect particles larger than 50 μm if the particle density is low and down to 10 μm if the matter is reasonably dense. Though other efficient devices are available in recent days, certain advantages with settling chambers suggest their adoptability for specific use. In certain cases settling chamber by itself is sufficient to control pollution adequately. If, however, still smaller particles are to be removed, the settling chamber is used as a concentrator or a primary collection device followed by a more efficient one, thus reducing the overall cost. Settling chambers need low installation, maintenance and energy costs and it has excellent reliability.

The design of settling chamber is based on particle settling principle. A particle entering into a chamber moves with a velocity with its horizontal and vertical components equal to gas velocity and the particle terminal settling velocity respectively. For laminar flow conditions within a settling chamber there is a minimum or limiting size of particles that settle completely, while particles smaller than this size settle partially. The amount of particles collected out of the total entering into the settling chamber, accounts for its collection efficiency. For a given flow rate, the smaller particles require larger settling surface area for their removal. Hence, for high collection efficiency or a large flow rate, or both, the required length and breadth of the collection tray of the chamber becomes very large. In this case, a single tray settling chamber occupies a large land area, which may not be economical. Use of multiple trays spaced one above the other, improves the efficiency by increasing the collection surface area, and cuts down land area requirement. The exhaust gas enters into the settling chamber with certain dust loading. The particles settle in layers on the collection trays that must be removed periodically for maintaining desired efficiency. High gas velocity inside the settling chamber causes turbulent eddies, which pick up the settled particles and reentrain them into the flowing gas, thus reducing the collection efficiency. Hence, the gas velocity inside the chamber should be so maintained that there is no reentrainment of particles. The settling chambers are usually made of metal that need to withstand high temperature of the exhaust gas. Besides, various structural members of the settling chamber are subjected to stresses while in service. These devices should be structurally safe as well as cost effective.

An optimal design should address all the above fluid dynamic and structural aspects and yield minimum cost. This can be achieved by formulating the design problem as a constrained minimization problem and to develop a suitable algorithm to solve it with minimum computational time.

Structural configuration

A rectangular box type settling chamber (Fig. 1) made of cold formed strip steel that withstands tensile and compressive stresses in reasonably large temperature range, was considered in the design. Each collection tray was considered to be supported by a pair of symmetrical I-beams transferring load to light gauge columns having box section with breadth/width ratio as 2:1. For structural stability, the columns were extended up to the top of the chamber. The beams and the two sides were assumed fastened with columns using suitable fasteners. The top, front and rear, and the two sides of the chamber were considered to be provided with strip steel sheets of nominal thickness of 2 mm.

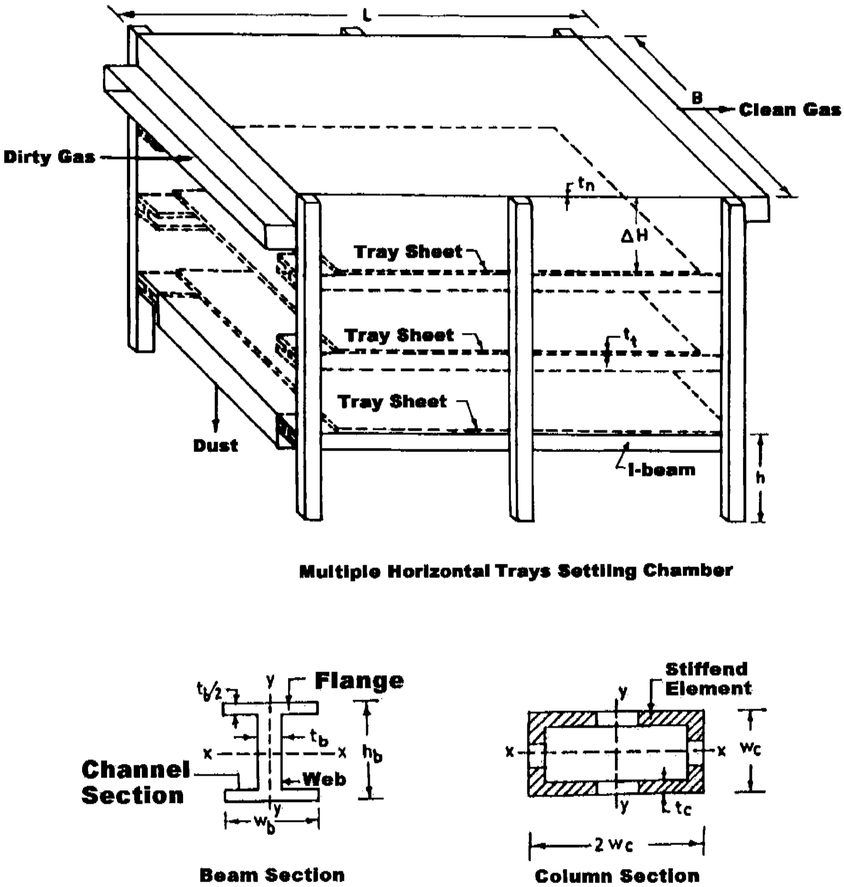

Figure 1: Schematic diagram of a settling chamber

For a flow rate, a designer is left with various options in deciding the number of units (settling chamber) to be adopted. It is found that sometimes, more than one smaller unit kept in parallel is economical than a single large unit.

Cost function

The cost of settling chamber (Fig. 1) comprises the cost of beams, columns, tray sheets, and top and side sheets (neglecting the entry and exit openings). The cost function F was obtained as:

$$F = NC_s\{t_n[BL + 2B(H + N_t t_t) + 2L(H + N_t t_t)] + N_t BLt_t + 2N_t Lt_b(w_b + h_b - t_b) + 4t_c(N_S + 1)(3w_c - 2t_c)[H + h + N_t t_t + t_n]\} \quad (1)$$

in which L = length; B = width and H = height of chamber; t_n = nominal thickness of the side sheets; t_t = thickness of tray sheet; w_b = flange width; h_b =

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height and t_b = web thickness of I-beam; w_c = width; t_c = thickness and h = height of column; N = number of parallel units of settling chambers; N_s = number of beam spans; N_t = number of tray sheets; and C_s = cost per unit volume of steel.

Description of constraints

The design should satisfy the following constraints:

A. Fluid dynamic constraints

To satisfy the functional requirements, the design should satisfy the following fluid dynamic criteria:

1. Flow regime

The dust laden gas enters into the settling chamber and the solid particles settle over the collection trays forming layers, which are to be removed at pre-decided intervals. As the particle size is very small, the turbulent fluctuations keep the particles well mixed in the gas stream. For gravitational settling, the turbulent fluctuations are to be kept at minimum. This can be achieved by limiting the flow Reynolds number to 4000, i.e.

$$\frac{0.0005 Q \rho_P (1-\in) BL}{\left[\rho_P NBL(1-\in)(N_t B + H) - 3600 \eta_D C Q t_d\right] v} \leq 1 \tag{2}$$

in which ρ_p = mass density of particles; Q = gas flow rate; and v = kinematic viscosity of gas; t_d = cleaning interval in hour; $\in$ = porosity of deposited material; C = mass-volume concentration of particles; and η_D = design efficiency of settling chamber.

2. Collection efficiency

For laminar flow conditions, Bhattacharjee [1] derived an explicit equation for collection efficiency of the settling chamber using the settling criteria given by Camp [2] and a particle probability distribution [5] given by Swamee and Ojha [6]. The collection efficiency of the settling chamber should be greater than or equal to the design efficiency, η_D, i.e.,

$$\eta_D + \frac{2}{m+2}\left(\frac{18 \rho_g v Q}{\rho_P g N N_t B L d_*^2}\right)^{0.5m} \leq 1 \tag{3}$$

in which ρ_g = mass density of gas; g = gravitational acceleration; m and d_* = size distribution parameters describing a particle size distribution.

3. Reentrainment of particles

High gas velocity causes formation of turbulent eddies which reentrain the particles already settled. Ingersoll et. al. [4] gave the following criterion for preventing reentrainment

$$\frac{u_*}{\omega_o} \leq k \tag{4a}$$

in which ω_o = fall velocity corresponding to minimum particle size d_o which is to be retained in the chamber; k = a constant, ranging between 0.5 and 0.83 and u_* = shear velocity, given by

$$u_* = \frac{Q}{NBH}\left(\frac{f}{8}\right)^{0.5} \tag{4b}$$

in which f = the Darcy-Weisbach friction factor. For the particle of size d_o to settle within the settling length L

$$\omega_o = \frac{Q}{NN_t BL} \tag{4c}$$

Substituting eqn (4b) and eqn (4c) in (4a) and making allowance for the deposited bulk of particles [3], the criterion for preventing reentrainment was obtained as

$$\frac{\rho_P(1-\in)NN_t BL^2}{k\left[N\rho_P(1-\in)HBL - 3600\eta_D CQt_d\right]}\left[\frac{f}{8}\right]^{0.5} \leq 1 \tag{4d}$$

B. Structural constraints

To satisfy the structural safety conditions, the design should satisfy the following requirements:

(a) Tray Sheet

1. Bending stress

The bending stress of tray sheet should be less than or equal to allowable bending stress F_{bt} this condition was written as

$$\frac{0.75gB^2}{N_t F_{bt} t_t^2}\left[(1-\in)\rho_P H + \rho_s N_t t_t\right] \leq 1 \tag{5}$$

in which ρ_S = mass density of steel.

2. Deflection

The maximum deflection of the tray sheet should be less than or equal to allowable deflection Δ_t. To limit the deflection within acceptable norm, Δ_t was taken as $2B/325$. Hence, the constraint reduced to

$$\frac{1625gB^3}{64N_t Et_t^3}\left[(1-\in)\rho_P H+\rho_s N_t t_t\right]\leq 1 \tag{6}$$

in which E = Young's modules of elasticity.

(b) I-beam

1. Bending stress

The bending stress of the beam should be less than or equal to allowable bending stress F_{bb} = 122.63 Mpa (cold formed steel), i.e.,

$$\frac{0.75gh_b L^2}{F_{bb}N_t N_s^2}\left\{\frac{0.5B\left[(1-\in)H\rho_P+\rho_s N_t t_t\right]+\rho_s N_t t_b\left(w_b+h_b-t_b\right)}{w_b h_b^3-\left(w_b-t_b\right)\left(h_b-t_b\right)^3}\right\}\leq 1 \tag{7}$$

2. Deflection:

The deflection of the beam should be less than or equal to allowable deflection Δ_b. This condition can be written as:

$$\frac{5gL^4}{32\Delta_b EN_t N_s^4}\left\{\frac{0.5B\left[(1-\in)\rho_P H+\rho_s N_t t_t\right]+\rho_s N_t t_b\left(w_b+h_b-t_b\right)}{w_b h_b^3-\left(w_b-t_b\right)\left(h_b-t_b\right)^3}\right\}\leq 1 \tag{8}$$

Δ_b was taken as $L/(325N_s)$.

3. Shear stress

Beam shear should be less than or equal to allowable shear stress τ_{ba}, i.e.,

$$\frac{0.5gL}{N_t N_s \tau_{ba}}\left\{\frac{0.5B\left[(1-\in)\rho_P H+\rho_s N_t t_t\right]+\rho_s N_t t_b\left(w_b+h_b-t_b\right)}{t_b\left(h_b-t_b\right)}\right\}\leq 1 \tag{9}$$

for safe design, $\tau_{ba} = (2/3)\,F_{bb}$

(c) Box type column

1. Slenderness ratio

The slenderness ratio of the column should be less than of equal to the limiting slenderness ratio, i.e.,

$$\left\{\frac{6\sigma_y k_f h^2}{\pi^2 E}\left[\frac{t_c(3w_c - 2t_c)}{w_c^4 - (w_c - t_c)(w_c - 2t_c)^3}\right]\right\}^{0.5} \leq 1 \tag{10}$$

in which σ_y = minimum guaranteed yield stress; and k_f = form factor of column.

2. Overall buckling

The axial stress acting on the column should be less than or equal to allowable compressive stress F_{ca}, i.e.

$$\frac{g}{2t_c(3w_c - 2t_c)F_{ca}}\left\{\frac{0.5BL}{N_t N_s}\left[(1-\in)\rho_P H + \rho_s N_t t_t\right]\right.$$
$$\left. + \frac{\rho_s t_b L}{N_s}(w_b + h_b - t_b) + 2\rho_s t_c(3w_c - 2t_c)\left[H + h + N_t t_t + t_n\right]\right\} \leq 1 \tag{11a}$$

in which

$$F_{ca} = \frac{k_f \sigma_y}{F_s}\left\{1 - \frac{3\sigma_y k_f h^2}{\pi^2 E}\left[\frac{t_c(3w_c - 2t_c)}{w_c^4(w_c - t_c)(w_c - 2t_c)^3}\right]\right\} \tag{11b}$$

Design algorithm

As formulated in the preceding section, the optimal design of settling chamber boils down to minimization of F given by eqn (1) subject to the constraints (2), (3), (4d), (5), (6), (7), (8), (9), (10) and (11a). The random search method has been found successful for solving the problem of the present size and nature. In this method the design variables constitute a design vector V. With this vector, a random design was chosen by

$$V^{(r)} = V_L^{(r)} + \left(V_U^{(r)} - V_L^{(r)}\right)R \tag{12a}$$

in which $V_L^{(r)}$ = the lower bound of V; $V_U^{(r)}$ = the upper bound of V; R is a uniformly distributed random number varying between 0 and 1; and the superscript r denotes the number of cycles. The random design, thus obtained, was then reduced to the nearest commercially available design. Thus, for r = 0, an initial random design was obtained. This initial design was checked for the satisfaction of all the constraints. If any one of the constraints was violated, the

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design was rejected and a new random design was generated. This process was repeated till all the constraints were satisfied. Thus, an initial feasible design was obtained by eqn (1). The process was repeated to obtain another feasible design and its cost. If this cost was less than that of previously obtained feasible design, the current design vector and its cost were retained. The process was repeated for a large number of times. Subsequently, the search was refined by reducing the range of the design vector $V^{(r)}$ by

$$V_L^{(r+1)} = V^{(r)} - 0.45\left[V_U^{(r)} - V_L^{(r)}\right] \quad (12b)$$

$$V_U^{(r+1)} = V^{(r)} + 0.45\left[V_U^{(r)} - V_L^{(r)}\right] \quad (12c)$$

With the new range of design vector, the process was repeated for several cycles till the difference between the costs of two successive feasible designs was small. Use of this algorithm led to the design of a settling chamber that represented the one having least cost and satisfying the functional and structural safety requirements.

Design example

Design a multiple horizontal tray settling chamber to remove fly ash particles from an industrial emission flowing at the rate of 4 m^3/s with a dust loading of 0.15 kg/m^3. Take 92% design efficiency and 1 hour cleaning interval.

Using the algorithm, a settling chamber was designed with the following data: $Q = 4\ m^3/s$; $\rho_P = 2200\ kg/m^3$; $\rho_g = 1.18\ kg/m^3$; $\rho_s = 7850\ kg/m^3$; $\nu = 1.5\times10^{-5}\ m^2/s$; $h = 1$ m; $k = 0.83$; $k_f = 0.6$; $F_s = 2.16$; $F_{bt} = 161.8$ Mpa; $E = 204$ Gpa; $F_{bb} = 122.63$ Mpa; $\sigma_y = 227$ Mpa; $t_n = 2$ mm; $C = 0.15\ kg/m^3$; $t_d = 1$hr.; $f = 0.025$; and $\eta_D = 0.92$; $\in = 0.4$ and the particle size distribution parameter for fly ash: $d_* = 54$ µm; $m = 1.78$.

The following dimensions of the settling chamber were obtained:

Chamber: $L = 1.08$ m; $B = 0.48$ m; $H = 1.51$ m; $N_t = 15$; $t_t = 2$ mm; $N = 16$; Chamber height = 1.54 m.

Frame: Span - $N_s = 1$. I-beam - $w_b = 80$ mm; $h_b = 100$ mm; $t_b = 2$ mm. Box type columns - $w_c = 70$ mm; $t_c = 2$ mm; and breadth = 140 mm.

It was found that at optimality, the constraints given by (2), (3) and (5) were tight, while all other constraints were loose. Fig. 2 depicts the convergence of F with the number of cycles. It can be seen that F converges at a fast rate, and only a few cycles were needed to obtain the minima, thus requiring a small computational time.

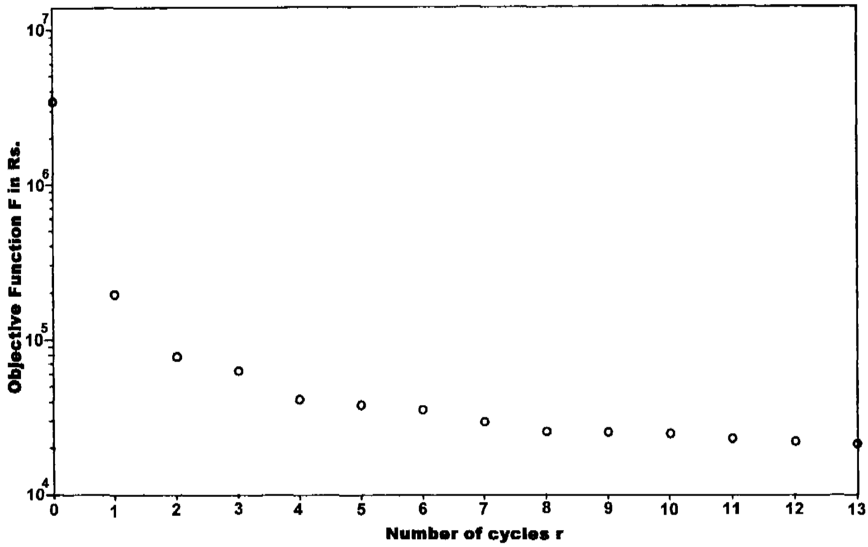

Figure 2: Convergence of algorithm

Conclusion

It has been possible to develop the design of a multiple trays settling chamber as a minimization problem involving non-linear objective function and constraints. Random search method has been found successful in obtaining the minima.

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